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Scoping Review with Topic Modeling on the Diagnostic Criteria for Degenerative Cervical Myelopathy

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Abstract

Study Design: This study is a scoping review.

Objective: There is a broad variability in the definition of degenerative cervical myelopathy (DCM) and no standardized set of diagnostic criteria to date.

Methods: We interrogated the Myelopathy.org database, a hand-indexed database of primary clinical studies conducted exclusively on DCM in humans between 2005-2021. The DCM inclusion criteria used in these studies were inputted into 3 topic modeling algorithms: Hierarchical Dirichlet Process (HDP), Latent Dirichlet Allocation (LDA), and BERtopic. The emerging topics were subjected to manual labeling and interpretation.

Results: Of 1676 reports, 120 papers (7.16%) had well-defined inclusion criteria and were subjected to topic modeling. Four topics emerged from the HDP model: disturbance from extremity weakness and motor signs; fine-motor and sensory disturbance of upper extremity; a combination of imaging and clinical findings is required for the diagnosis; and "reinforcing" (or modifying) factors that can aid in the diagnosis in borderline cases. The LDA model showed the following topics: disturbance to the patient is required for the diagnosis; reinforcing factors can aid in the diagnosis in borderline cases; clinical findings from the extremities; and a combination of imaging and clinical findings is required for the diagnosis. BERTopic identified the following topics: imaging abnormality, typical clinical features, range of objective criteria, and presence of clinical findings.

Conclusions: This review provides quantifiable data that only a minority of past studies in DCM provided meaningful inclusion criteria. The items and patterns found here are very useful for the development of diagnostic criteria for DCM.

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Keywords
cervical, degenerative, disc herniation, spinal cord injury, magnetic resonance imaging, myelopathy

Introduction

Background

Degenerative cervical myelopathy (DCM) is the most common non-traumatic cause of cervical spinal cord dysfunction in adults worldwide.[1-5] During the last 2 decades, there has been an exponential increase in the number of published studies regarding DCM.[6,7] This is not surprising considering that recent estimates suggest DCM could affect 2.3% in a healthy population.[3,4,8,9] Furthermore, DCM can cause significant disability, result in loss of independence and impose substantial financial burden.

Timely diagnosis has emerged as a key priority for DCM, given that duration of symptoms is currently one of the only modifiable predictors of surgical outcomes.[10-14] Recent estimates suggest that up to 90% of DCM is undiagnosed,[15-18] and that individuals may wait 2 to 5 years [19] to obtain a correct diagnosis. Despite these shortcomings, there is still no agreement in the literature on what constitutes DCM or even a standardized nomenclature in the field. This is a challenge in both a research setting and clinical practice and may impede the education of health care providers who first encounter such patients, such as primary care physicians and allied professionals.

Reviewing the inclusion criteria used for clinical research studies may offer a perspective on how DCM should be defined. Previous analysis used to inform the consensus adoption of an index term for DCM and form a minimum dataset suggests that the criteria used to enroll patients into research studies is heterogeneous and may vary substantially.[20,21] However, aggregating this content and employing new natural language processing (NLP) methods could offer collective insights into how the field diagnoses DCM.

The authors of the current work hypothesize that DCM criteria used over the past decades highly vary in content and precision, since there is no standardized definition for DCM. However, common patterns in inclusion criteria from previous studies may be used to better define DCM. The objective of this study is (i) to demonstrate the infrequent use of well-defined and reproducible DCM criteria and (ii) to scope the literature and apply topic modeling methodology to map the patterns that have been used as inclusion criteria in primary DCM studies. Essentially, the reported diagnostic criteria will be used as a "proxy" to reflect existing DCM diagnostic criteria used in medical literature.

Methods

Eligibility Criteria and Information Sources

For this work, primary human studies that included 15 or more subjects with DCM qualified for inclusion. Studies were only considered if they utilized predetermined clinical, radiological, and/or surgical criteria in order to select their patient population. Studies were excluded if they met any of the following criteria: (1) no inclusion or exclusion criteria provided in the methods section, (2) the authors provided relevant clinical features of their patients in the methods section but did not specifically report inclusion criteria, (3) the study summarized inclusion criteria but did not distinguish between patients with traumatic vs non-traumatic myelopathy or between patients with myelopathy vs radiculopathy, (4) only nonspecific inclusion criteria were provided (tautological, eg, "signs and symptoms typical for DCM"), (5) the study only reported a standardized scale (eg, modified Japanese Orthopedic Association (m)JOA) score) as a way of qualifying patients' neurologic function, (6) the study was a review article, animal study, survey, editorial or commentary. If studies were based on data from the same dataset, only one was included in this scoping review. Lastly, only reports in the English language were considered. This review aligns with research Priority 3: Diagnostic Criteria of AO Spine RECODE-DCM.[17] Since this is a scoping review and no identifiable patient information was accessed, informed consent and institutional review board approval were not necessary.

Search Strategy

Myelopathy.org is a scientific and clinical charity dedicated to transforming outcomes in DCM through global research initiatives and by raising awareness among the public and health care professionals. Based on highly sensitive search filters for MEDLINE[22] and EMBASE,[23] a dataset of primary clinical articles exclusively on DCM was developed for the purpose of revealing insights into the research field, and supporting research.[6,7,24] For the purposes of this scoping review, this database was accessed in order to identify all DCM papers published between 2005 and 2021.

Study Selection

Based on the recognition that the abstracts would not contain the relevant information to judge the inclusion criteria, full-text review was completed to screen for eligible studies. The rationale for this was that the authors' primary purpose was to identify any possible DCM definitions across all published primary studies. Such definitions, if provided by the authors of each study, were expected to be found in the methods section of each report. Hence, screening by title/abstract was not relevant for the objective of this scoping review. Before screening, all reviewers were trained with a teach-back method from the senior authors on how to identify eligible

reports based on the predefined eligibility criteria. All papers were equally assigned to 7 independent reviewers. Any articles that were considered relevant by the reviewers were included. In order to assure relevancy, the definitions extracted from the included articles were reviewed by the senior authors.

Data Collection Process

The methods section of each report was screened and inclusion/exclusion criteria were extracted. A data collection tool was developed by the research team in order to standardize data extraction for studies that satisfied our inclusion criteria. Data obtained from each study included the following: name and country of first author, publication year, study design, sample size, inclusion/exclusion criteria and DCM definition. Due to the large number of studies, each report was reviewed by only one reviewer and one senior reviewer.

Data Preparation

The raw text of the inclusion criteria from each eligible study was collected. Parts of the criteria were deleted if they were specific for the purposes of a particular research study but not generalizable for the diagnosis of DCM. Specifically, parts that stated other neurological pathologies (eg, amyotrophic lateral sclerosis, multiple sclerosis) as exclusion criteria were removed. In individual studies, these exclusion criteria were used to create a more homogenous research population in order to avoid confounders. For the purpose of this scoping review, it was agreed that these parts of inclusion criteria were not useful and may introduce noise into the analysis. There is no fundamental reason why other neurological pathologies cannot develop in the presence of DCM. Furthermore, many studies excluded OPLL when screening for eligible patients despite the fact that OPLL is currently considered within the spectrum of DCM. Therefore, statements of exclusion of OPLL patients were also deleted for the purpose of this analysis.

Data Analysis

The authors used the following methods for data analysis: (1) Topic modeling with algorithms not based on transformers. Topic modeling is a NLP unsupervised method that identifies word and phrase patterns within texts, and automatically clusters these patterns. The Hierarchical Dirichlet Process (HDP), a nonparametric Bayesian approach to clustering grouped data, was utilized and implemented through the gensim Python package.[25] (2) Topic modeling with transformers-based algorithms. BERTopic for topic modeling is a newer topic modeling algorithm that incorporates the use of transformers, which is the current state of the art algorithm for NLP.[26] The transformers offer the capability to encode contextual information and do not require removal of stop words.[27] More details regarding these analyses have been included in the Supplemental Material.

Analysis of the Meaning of the Identified Topics

The topic that emerged from the above topic modeling algorithms were manually labeled. Specifically, the topic labels were determined based on the topic words and the sample vetting. The meaning of each topic label was interpreted by the senior authors and an overarching theme was selected for each topic using our domain expertise of a multi-stakeholder working group, the RECODE-DCM Diagnostic Criteria Incubator. The topics were named based on the content of each topic. The final determination was reached through a consensus process after several iterations of proposals.

Results

Scoping Review

In total, 1676 papers published between 2005 and 2021 were retrieved for consideration in this scoping review. Of these, 120 studies specified inclusion criteria and were eligible for topic modeling (Figure 1). The most common reasons for exclusion were the following: (1) no inclusion or exclusion criteria were provided in the methods section, (2) the study did not elaborate on the clinical definition of DCM, (3) the study summarized inclusion criteria, but did not distinguish between patients with traumatic vs non-traumatic myelopathy or between patients with myelopathy vs radiculopathy. Table 1 lists the title, journal and year of publication of each included study.

HDP Results

Four topics emerged from the HDP model and are presented as word clouds in Figure 2. Word clouds are graphical representations of words used in a particular context. The more a certain word or term is represented in a source text, the greater its prominence will be in the word cloud. For HDP Topic 0, disturbance from upper and lower extremity weakness in

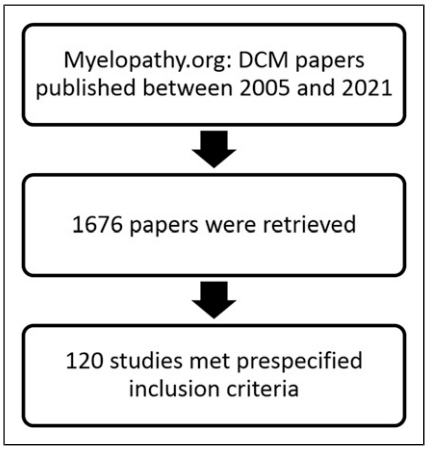

Figure 1. Diagram of the included studies.

Table 1. Title, Journal and Year of Publication of Each Included Study.

Study Number	Publication Year	Titles	Journal
1	2006	Corticospinal tract conduction block results in the prolongation of central motor conduction time in compressive cervical myelopathy.	Clinical neurophysiology
2	2006	Electrophysiological evidence of functional improvement in the corticospinal tract after laminoplasty in patients with cervical compressive myelopathy: Clinical article.	Journal of neurosurgery: Spine
3	2006	Evaluation of impairment of hand function in patients with cervical myelopathy.	Journal of spinal disorders and techniques
4	2006	The influence of proprioceptive impairment on hand function in patients with cervical myelopathy.	Spine
5	2006	Transcranial magnetic stimulation screening for cord compression in cervical spondylosis.	Journal of the neurological sciences
6	2007	Clinical and MRI predictors of outcome after surgical intervention for cervical spondylotic myelopathy.	Journal of neuroimaging
7	2007	Cervical corpectomy with preserved posterior vertebral wall for cervical spondylotic myelopathy: A randomized control clinical study.	Spine
8	2007	Cross-sectional transverse area and hyperintensities on magnetic resonance imaging in relation to the clinical picture in cervical spondylotic myelopathy.	Spine
9	2007	Laminoplasty and skip laminectomy for cervical compressive myelopathy: Range of motion, postoperative neck pain, and surgical outcomes in a randomized prospective study.	Spine
10	2007	Prognostic factors for deterioration of patients with cervical spondylotic myelopathy after nonsurgical treatment.	Spine
11	2007	Cutaneous silent periods in the evaluation of cord compression in cervical spondylosis.	Journal of neurology
12	2007	Technical modification and comparison of results with Hirabayashi's open-door laminoplasty.	Journal of Korean neurosurgical society
13	2007	Cervical spondylotic myelopathy due to chronic compression: The role of signal intensity changes in magnetic resonance images.	Journal of neurosurgery: Spine
14	2007	Open-door laminoplasty with suture anchor fixation for cervical myelopathy in ossification of the posterior longitudinal ligament.	Journal of spinal disorders and techniques
15	2007	Prognostic relevance of the postoperative evolution of intramedullary spinal cord changes in signal intensity on magnetic resonance imaging after anterior decompression for cervical spondylotic myelopathy.	Journal of neurosurgery: Spine
16	2008	Presymptomatic spondylotic cervical myelopathy: An updated predictive model.	European spine journal
17	2008	Somatosensory evoked potentials (SEPs) for the evaluation of cervical spondylotic myelopathy: Utility of the onset-latency parameters.	Clinical neurophysiology
18	2008	Impaired postural stability in patients with cervical myelopathy evaluation by computerized static stabilometry.	Spine
19	2008	Abnormal parameters of magnetically evoked motor-evoked potentials in patients with cervical spondylotic myelopathy.	Spine journal
20	2008	Stance ataxia and delayed leg muscle responses to postural perturbations in cervical spondylotic myelopathy.	Journal of rehabilitation medicine
21	2009	Evaluation of arthrodesis and cervical alignment in the surgical results of cervical discectomy using polymethylmetacrylate.	Arquivos de neuro-psiquiatria
22	2009	Multilevel oblique corpectomy without fusion in managing cervical myelopathy: Long-term outcome and stability evaluation in 268 patients - clinical article.	Journal of neurosurgery: Spine
23	2009	Anterior spinal fusion vs laminoplasty for cervical spondylotic myelopathy: a Retrospective review.	Journal of orthopaedic surgery (Hong Kong)
24	2009	Functional outcome of corpectomy in cervical spondylotic myelopathy.	Indian journal of orthopaedics
25	2009	Does walking change the romberg sign?.	European spine journal

(continued)

Table 1. (continued)

Study Number	Publication Year	Titles	Journal
26	2010	Resolution of physical signs and recovery in severe cervical spondylotic myelopathy after cervical laminoplasty.	Spine
27	2010	Clinical outcomes of microendoscopic decompression surgery for cervical myelopathy.	European spine journal
28	2010	Axial neck pain after cervical laminoplasty.	Journal of Korean neurosurgical society
29	2010	Clustered clinical findings for diagnosis of cervical spine myelopathy.	Journal of manual and manipulative therapy
30	2010	Cervical myelopathy: A clinical and radiographic evaluation and correlation to cervical spondylotic myelopathy.	Spine
31	2011	Surgical treatments of myelopathy caused by cervical ligamentum flavum ossification.	World neurosurgery
32	2011	Diffusion tensor imaging in the cervical spinal cord.	European spine journal
33	2011	Quantification of the tromner signs: A sensitive marker for cervical spondylotic myelopathy.	European spine journal
34	2011	Relative vulnerability of various spinal tracts in C3-4 cervical spondylotic myelopathy: Multi-modal spinal cord evoked potentials.	Spinal cord
35	2012	Comparison between anterior and posterior decompression for cervical spondylotic myelopathy: Subjective evaluation and cost analysis.	Orthopaedic surgery
36	2012	Is surgery for cervical spondylotic myelopathy cost-effective? A cost-utility analysis based on data from the AOSpine north America prospective CSM study.	Journal of neurosurgery: Spine
37	2012	Gait impairment in cervical spondylotic myelopathy: Comparison with age- and gender-matched healthy controls.	European spine journal
38	2012	Risk factors for acute cervical spinal cord injury associated with ossification of the posterior longitudinal ligament.	Spine
39	2012	The epidemiology of cervical spondylotic myelopathy.	Skeletal radiology
40	2012	Investigation of segmental motor paralysis after cervical laminoplasty using intraoperative spinal cord monitoring with transcranial electric motor-evoked potentials.	Journal of spinal disorders and techniques
41	2013	Evaluation of conservative treatment and timing of surgical intervention for mild forms of cervical spondylotic myelopathy.	Experimental and therapeutic medicine
42	2013	Long-term follow-up results of the cloward procedure for cervical spondylotic myelopathy.	European spine journal
43	2013	Influence of intramedullary stress on cervical spondylotic myelopathy.	Spinal cord
44	2013	Surgically treated cervical myelopathy: A functional outcome comparison study between multilevel anterior cervical decompression fusion with instrumentation and posterior laminoplasty.	Spine journal
45	2013	Correlation of magnetic resonance diffusion tensor imaging and clinical findings of cervical myelopathy.	Spine journal
46	2013	Clinical correlation of cervical myelopathy and the hyperactive pectoralis reflex.	Journal of spinal disorders and techniques
47	2014	Laminar reclosure after single open-door laminoplasty using titanium miniplates vs suture anchors.	Orthopedics
48	2014	Preoperative predictors of patient satisfaction with outcome after cervical laminoplasty.	Global spine journal
49	2014	Cervical spondylotic myelopathy surgical trial: Randomized, controlled trial design and rationale.	Neurosurgery
50	2015	Prediction of myelopathic level in cervical spondylotic myelopathy using diffusion tensor imaging.	Journal of magnetic resonance imaging
51	2015	The relation between location of cervical cord compression and the location of myelomalacia.	Skeletal radiology

(continued)

Table 1. (continued)

Study Number	Publication Year	Titles	Journal
52	2015	A clinical prediction rule for functional outcomes in patients undergoing surgery for degenerative cervical myelopathy: Analysis of an international prospective multicenter data set of 757 subjects.	J bone joint surg Am
53	2015	Prevalence and distribution of thoracic and lumbar compressive lesions in cervical spondylotic myelopathy.	Asian spine journal
54	2015	Relationship between signal changes on T2-weighted magnetic resonance images and cervical dynamics in cervical spondylotic myelopathy.	Journal of spinal disorders and techniques
55	2015	Postoperative three-dimensional cervical range of motion and neurological outcomes in patients with cervical ossification of the posterior longitudinal ligament: Cervical laminoplasty vs laminectomy with fusion.	Clinical neurology and neurosurgery
56	2015	Clinical and radiological characteristics of ossification of the posterior longitudinal ligament of the cervical spine in patients without myelopathy:results of a 1-year pilot study.	Turk neurosurg
57	2015	Transcranial magnetic stimulation in the diagnosis of cervical compressive myelopathy: Comparison with spinal cord evoked potentials.	Spine
58	2015	Gait analysis in cervical spondylotic myelopathy.	Asian spine journal
59	2015	Rapid progressive clinical deterioration of cervical spondylotic myelopathy.	Spinal cord
60	2015	Electrophysiological assessments of the motor pathway in diabetic patients with compressive cervical myelopathy.	Journal of neurosurgery: Spine
61	2015	Efficacy of posterior segmental decompression surgery for pincer mechanism in cervical spondylotic myelopathy: A retrospective case-controlled study using propensity score matching.	Spine
62	2015	Accuracy of diffusion tensor imaging for diagnosing cervical spondylotic Myelopathy in patients showing spinal cord compression	Korean J radiol.
63	2015	Modified expansive open-door laminoplasty technique improved postoperative neck pain and cervical range of motion.	J formos med assoc
64	2015	Correlation of cord signal change with physical examination findings in patients with cervical myelopathy.	Spine
65	2016	Amplitude of low frequency fluctuation (ALFF) in the cervical spinal cord with stenosis: A resting state fMRI study.	PLoS ONE
66	2016	Functional and radiological outcome in patients undergoing 3 level corpectomy for multi-level cervical spondylotic myelopathy and ossified posterior longitudinal ligament.	Neurology India
67	2016	High incidence of undiagnosed cervical myelopathy in patients with hip fracture compared with controls.	Journal of orthopaedic trauma
68	2017	Diagnosis and treatment of hidden lesions in "mild" cervical spondylotic myelopathy patients with apparent symptoms.	Medicine
69	2017	Safety and efficacy study of an ozone laser combined therapy using puncture needle in the treatment of patients with cervical spondylosis.	Clinical spine surgery
70	2017	Anterior cervical discectomy and fusion provides better surgical outcomes than posterior laminoplasty in elderly patients with C3-4 level myelopathy.	Spine
71	2017	Correlation analysis between modic change of cervical vertebrae and intramedullary high signal intensity.	Clinical spine surgery
72	2017	Myelopathy associated with age-related cervical disc herniation: a Retrospective review of magnetic resonance images.	Annals of saudi medicine
73	2017	The assessment of upright cervical spinal alignment using supine MRI studies.	Clinical spine surgery
74	2017	Use of central motor conduction time and spinal cord evoked potentials in the electrophysiological assessment of compressive cervical myelopathy.	Spine
75	2017	Kinematic effects of cervical laminoplasty for cervical spondylotic myelopathy on the occipitoatlantoaxial junction.	Clinical spine surgery
76	2017	The significance of the tromner sign in cervical spondylotic myelopathy patient.	Clinical spine surgery

(continued)

Table 1. (continued)

Study Number	Publication Year	Titles	Journal
77	2018	Tract-specific volume loss on 3T MRI in patients with cervical spondylotic myelopathy.	Spine
78	2018	Quantitative magnetization transfer MRI measurements of the anterior spinal cord region are associated with clinical outcomes in cervical spondylotic myelopathy.	Spine
79	2018	Poorer fusion outcomes in diabetic cervical spondylotic myelopathy patients undergoing single-level anterior cervical discectomy and fusion does not compromise functional outcomes and quality of life.	Spine
80	2019	Comparison of 10-year outcomes of bryan cervical disc arthroplasty for myelopathy and radiculopathy.	Orthopaedic surgery
81	2019	Clinical and radiographic outcome of patients with cervical spondylotic myelopathy undergoing total disc replacement.	Spine
82	2019	Association of VDR-FokI and VDBP-Thr420Lys polymorphisms with cervical spondylotic myelopathy: A case-control study in the population of China.	Journal of clinical laboratory analysis
83	2019	Recovery process after anterior cervical decompression in patients with cervical spondylotic myelopathy with different natural history.	Clinical spine surgery
84	2019	Assessing hand dysfunction in cervical spondylotic myelopathy.	PLoS ONE
85	2019	Clinical and radiographic outcome of patients with cervical spondylotic myelopathy undergoing total disc replacement.	Spine
86	2019	Risk factors for rapidly progressive neurological deterioration in cervical spondylotic myelopathy.	Spine
87	2019	Comparison of 10-year outcomes of bryan cervical disc arthroplasty for myelopathy and radiculopathy.	Orthopaedic surgery
88	2016	Identification of head control deficits following anterior cervical discectomy and fusion in patients with cervical spondylotic myelopathy.	European spine journal
89	2016	Hybrid decompression and fixation technique for the treatment of multisegmental cervical spondylotic myelopathy.	International journal of spine surgery
90	2016	Validation of the reliability of the Thai version of the Japanese orthopaedic association cervical myelopathy evaluation questionnaire (JOACMEQ).	Journal of orthopaedic science
91	2016	Effect of double-door laminoplasty on atypical symptoms associated with cervical spondylotic myelopathy/radiculopathy.	BMC surgery
92	2017	Correlation between diffusion tensor imaging parameters and clinical assessments in patients with cervical spondylotic myelopathy with and without high signal intensity.	Spinal cord
93	2017	Imaging factors that distinguish between patients with asymptomatic and symptomatic cervical spondylotic myelopathy with mild to moderate cervical spinal cord compression.	Medical science monitor
94	2017	Trans-synaptic degeneration of motoneurons distal to chronic cervical spinal cord compression in cervical spondylotic myelopathy.	International journal of neuroscience
95	2017	Microendoscopic laminotomy vs conventional laminoplasty for cervical spondylotic myelopathy: 5-year follow-up study.	Journal of neurosurgery: Spine
96	2017	Cervical radiculopathy combined with cervical myelopathy: Prevalence and characteristics.	European journal of orthopaedic surgery and traumatology
97	2017	Clinical predictors of surgical outcomes and imaging features in single segmental cervical spondylotic myelopathy with lower cervical instability.	Medical science monitor
98	2017	The functional relevance of diffusion tensor imaging in comparison to conventional MRI in patients with cervical compressive myelopathy.	Skeletal radiology
99	2017	Diffusion tensor imaging correlates with short-term myelopathy outcome in patients with cervical spondylotic myelopathy.	World neurosurgery
100	2018	Longitudinal brain activation changes related to electrophysiological findings in patients with cervical spondylotic myelopathy before and after spinal cord decompression: An fMRI study.	Acta neurochirurgica

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Table 1. (continued)

Study Number	Publication Year	Titles	Journal
101	2018	Role of cerebrolysin in cervical spondylotic myelopathy patients: a Prospective randomized study.	Spine journal
102	2018	Effect of osteoprotegerin gene polymorphisms on the risk of cervical spondylotic myelopathy in a Chinese population.	Clinical neurology and neurosurgery
103	2018	Stenosis and neurologic level discrepancies in cervical spondylotic myelopathy.	PM and R
104	2018	Visual cortex neural activity alteration in cervical spondylotic myelopathy patients: a resting-state fMRI study.	Neuroradiology
105	2018	Fractional anisotropy to quantify cervical spondylotic myelopathy severity.	Journal of neurosurgical sciences
106	2018	Fatty infiltration of the cervical multifidus musculature and their clinical correlates in spondylotic myelopathy.	Journal of clinical neuroscience
107	2018	The effect of intramedullary signal intensity in MRI on the therapeutic efficacy of posterior cervical decompression laminectomy with internal fixation and fusion for multi-level cervical spondylotic myelopathy: a Retrospective cohort study.	Acta orthopaedica belgica
108	2019	Changes in diffusion tensor imaging indices of the lumbosacral enlargement correlate with cervical spinal cord changes and clinical assessment in patients with cervical spondylotic myelopathy.	Clinical neurology and neurosurgery
109	2019	MR diffusion tensor imaging of the spinal cord: can it help in early detection of cervical spondylotic myelopathy and assessment of its severity?.	Egyptian journal of radiology and nuclear medicine
110	2019	Characterizing gait abnormalities in patients with cervical spondylotic myelopathy: a Neuromuscular analysis.	Spine journal
111	2019	Machine learning for the prediction of cervical spondylotic myelopathy: A post hoc pilot study of 28 participants.	World neurosurgery
112	2019	Rationales for a urodynamic study in patients with cervical spondylotic myelopathy.	World neurosurgery
113	2019	Assessment of spinal cord relative vulnerability in C4-C5 compressive cervical myelopathy using multi-modal spinal cord evoked potentials and neurological findings.	Journal of spinal cord medicine
114	2020	The frequency of various "myelopathic symptoms" in cervical myelopathy: Evaluation in a large surgical cohort.	Clinical spine surgery
115	2020	Characteristics of upper limb impairment related to degenerative cervical myelopathy: Development of a sensitive hand assessment (graded redefined assessment of strength, sensibility, and prehension version myelopathy).	Clinical neurosurgery
116	2020	Quantitative assessment of gait characteristics in degenerative cervical myelopathy: A prospective clinical study.	Journal of clinical medicine
117	2020	Functional connectivity changes of the visual cortex in the cervical spondylotic myelopathy patients: A resting-state fMRI study.	Spine
118	2020	Neural cell adhesion molecule (NCAM) a serum biomarker indicative for the severity of cervical spondylotic myelopathy.	Clinical spine surgery
119	2020	Morphologic characteristics of the deep cervical paraspinal muscles in patients with single-level cervical spondylotic myelopathy.	World neurosurgery
120	2020	Comparing clinical outcomes of using 3 vs 5 titanium miniplates in laminoplasty for multilevel cervical myelopathy: A prospective cohort study.	Journal of orthopaedic translation

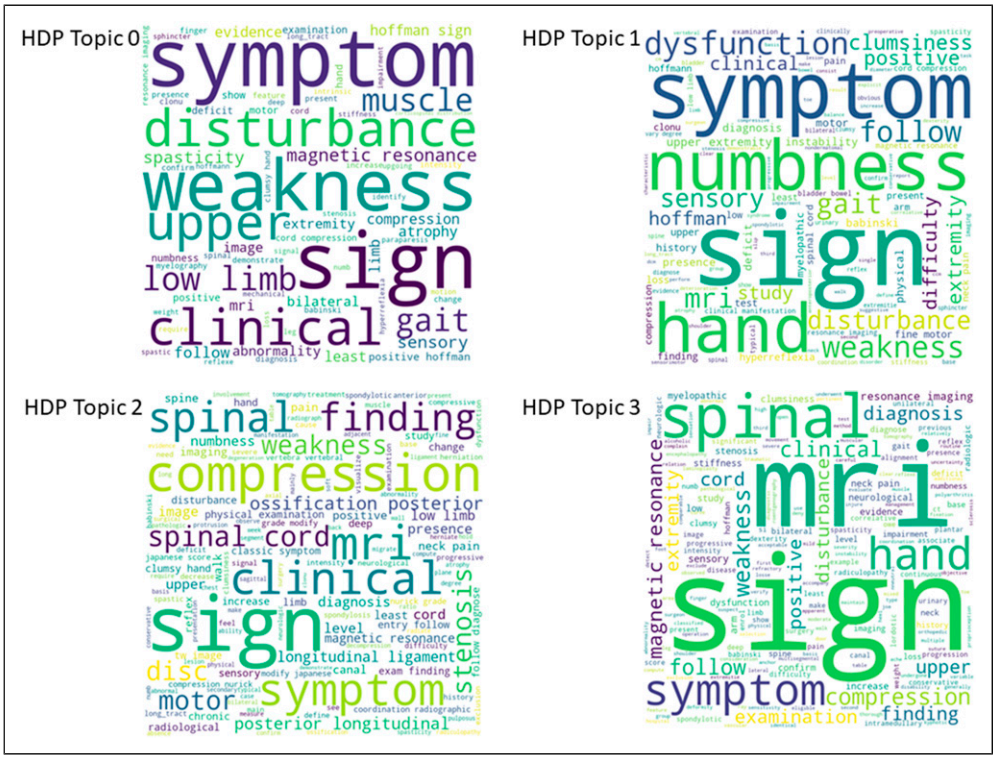

Figure 2. Word clouds produced for the HDP model topics.

addition to motor signs emerged as dominant findings (ie, and not sensory disturbance). For HDP Topic 1, fine-motor and sensory disturbance of the upper extremity were considered important. For HDP Topic 2, there was an equal representation of imaging (eg, compression, MRI) and clinical (eg, weakness, motor symptoms and signs) terms, suggesting that a combination of imaging and clinical findings is required for a diagnosis of DCM. The interpretation of the HDP Topic 3 is more challenging given the variety of terms including severity, progression, alignment, instability, objective findings (eg, MRI, clinical signs), and intramedullary. These terms appear totally disconnected; however, the emerging theme is that these might be "reinforcing" (or modifying) factors that can aid in the diagnosis of borderline cases. An additional LDA sensitivity analysis was conducted yielding word clouds model topics (Figure 3) and is described in the Supplemental Material in more detail. In Figures 2 and 3, words with greater size have been identified proportionally greater frequently within all the included papers.

BERTopic Results

BERTopic identified 4 topics (Figure 4). Topic 0 was automatically classified by the algorithm as "cord_compression_imaging" based on the most common words. This topic indicates that the presence of imaging findings is necessary for the diagnosis of DCM. Topic 1 was "weakness_signs_symptoms" and summarized the typical clinical features of DCM including both signs and symptoms. Topic 2 label was generated as "compression_cord_gait" and represents the range of objective criteria needed for the diagnosis of DCM. Finally, Topic 3 or "symptoms_bilateral_weakness" represented the need for the presence of clinical findings. Hierarchical clustering (Figure 5) showed proximity of topics 0 and 2 as well as topics 1 and 3. Topic clustering (Figure 6) showed significant overlap of topics 0 and 2. The distribution of topics over time (Figure 7) showed a volatility in topic 0. Similarly, the distribution of topics in the various journals (Figure 8) demonstrated a high frequency of topic 0 in journals dedicated to spine surgery.

Discussion

Degenerative cervical myelopathy is a common but poorly characterized non-traumatic spine disorder. Based on the findings of this scoping review, less than 10% of studies from the past decades used a reproducible set of inclusion criteria. The majority of the reviewed studies included generic statements about DCM, such as "patients with DCM were included", which were considered ill-defined and not reproducible. Given this heterogeneity, there is a pressing need to develop a widely accepted and standardized definition of DCM and create criteria to support timely diagnosis of this condition. Diagnostic criteria will improve consistency among studies and strengthen the external validity of future research endeavors. In prior work by Nouri et al, the term DCM was introduced as an overarching definition to describe

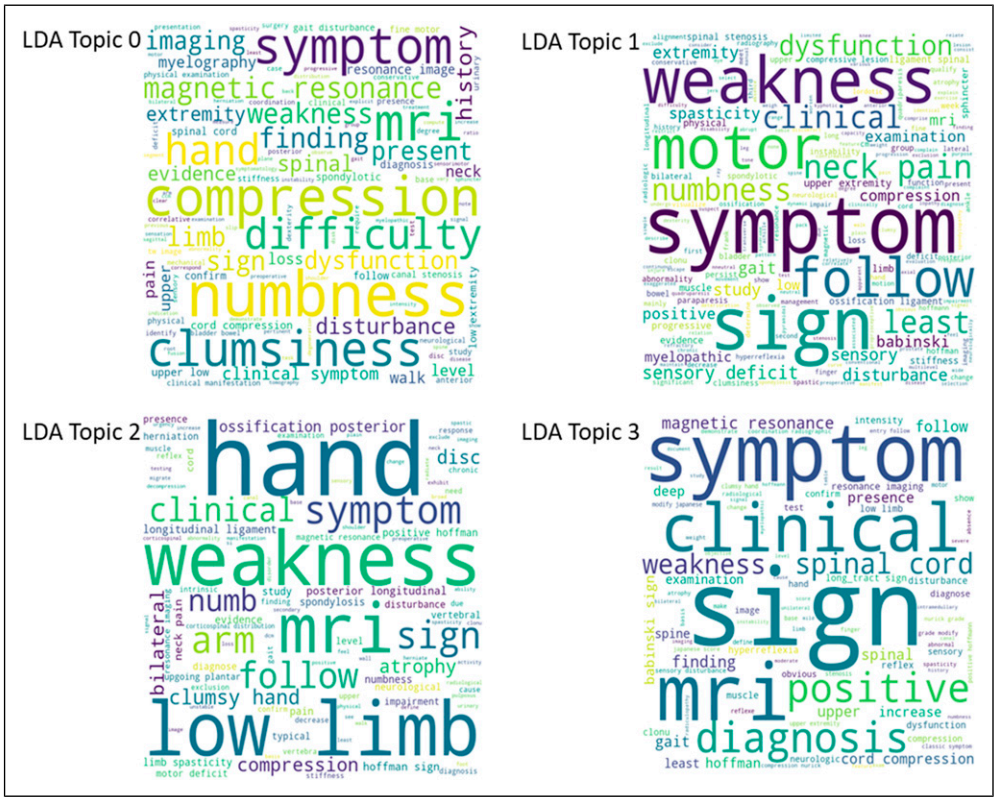

Figure 3. Word clouds produced for the LDA model topics.

Topic 0 representative documents: ['The patients with cervical myelopathy and spinal cord compression seen in MRI were studied.',
'Suspected cervical spondylopathy (due to a wide range of complaints from simple neck pain to motor weakness) were included in this study.',
'Patients with CSM with obvious cervical myelopathy symptoms such as upper-extremity clumsiness and gait instability.']
Topic 0 words: [cord, compression, imaging, pain, resonance, magnetic, signs, clinical, sensory, disturbance, all, presence, gait, upper, examination, confirmed, ossification, spine, t2, motor]
Possible overarching theme: imaging abnormality

Topic 1 representative documents: ['Typical clinical features included sensory defect; decreased muscle strength; and disturbance in gait, urination, and defecation.',
'(3) Unambiguous sensory symptoms or signs of the upper limb',
'Patients will have >2 of the following symptoms or signs: clumsy hands, gait disturbance, hyperreflexia, upgoing toes, bladder dysfunction, or ankle clonus.']
Topic 1 words: [signs, weakness, symptoms, disturbance, hands, positive, limb, lower, test, reflexes, numbness, clumsy, spasticity, hoffman, motor, stiffness, included, walking, clonus, babinski]
Possible overarching theme: Typical clinical features

Topic 2 representative documents: ['Inclusion criteria for entry included the following in all patients diagnosed with CSM: classic CSM symptoms, including exam findings of weakness, hyperreflexia, or change in coordination; radiographic signs of spinal compression; Nurick grade I-IV; and modified Japanese Orthopedic Association (mJOA) scores of <18.',
'Inclusion criteria for entry included the following in all patients diagnosed with CSM: classic CSM symptoms, including examination findings of weakness, hyperreflexia, or change in coordination; radiographic signs of spinal compression; Nurick grade I-IV; and modified Japanese Orthopedic Association (mJOA) scores of <18.',
'The inclusion criteria were as follows: CSM at admission; chronic shoulder and cervical pain, stiffness, limb pain/numbness/debilitation/muscular atrophy, and other typical clinical manifestations of CSM; vertebral hyperostosis, vertebral instability, disc herniation, and other typical imaging characteristics of cervical syndrome; and availability of complete clinical, preoperative flexion-extension plain radiography and MRI data.']
Topic 2 words: [compression, cord, gait, weakness, positive, motor, symptoms, association, japanese, orthopedic, typical, had, increased, sign, disc, stenosis, hyperreflexia, findings, radiographic, 18]
Possible overarching theme: range of objective criteria

Topic 3 representative documents: ['clinical and radiological evidence of CSM',
'The diagnosis of C3-4 CSM was made based on two key clinical findings, namely hyperreflexia of deep tendon reflexes of the brachioradialis and of the triceps and magnetic resonance imaging (MRI) localization of the most severe cord compression at the C3-4 levels, regardless of multiple stenosis.',
'Clinical diagnostic criteria for CSM included sensory impairments, muscular weakness, or associated hyperreflexia in upper and lower extremities.']
Topic 3 words: [symptoms, bilateral, weakness, radiological, spasticity, limb, atrophy, positive, motor, evidence, sign, required, least, made, cord, hands, neuron, numb, hyperreflexia, compression]
Possible overarching theme: presence of clinical findings

Figure 4. Key characteristics of the topics that emerged with BERTopic.

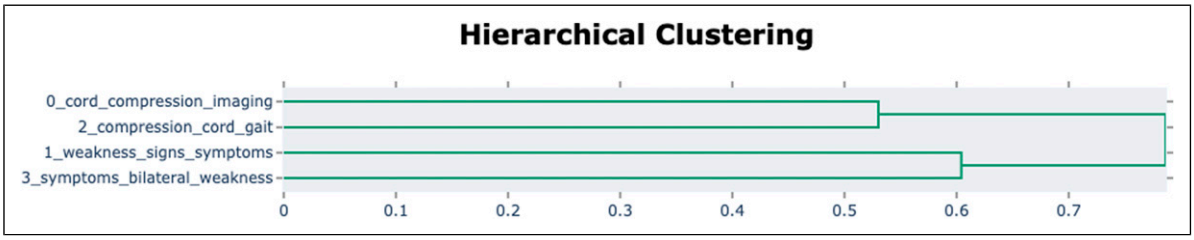

Figure 5. Hierarchical clustering of the BERTopic model topics.

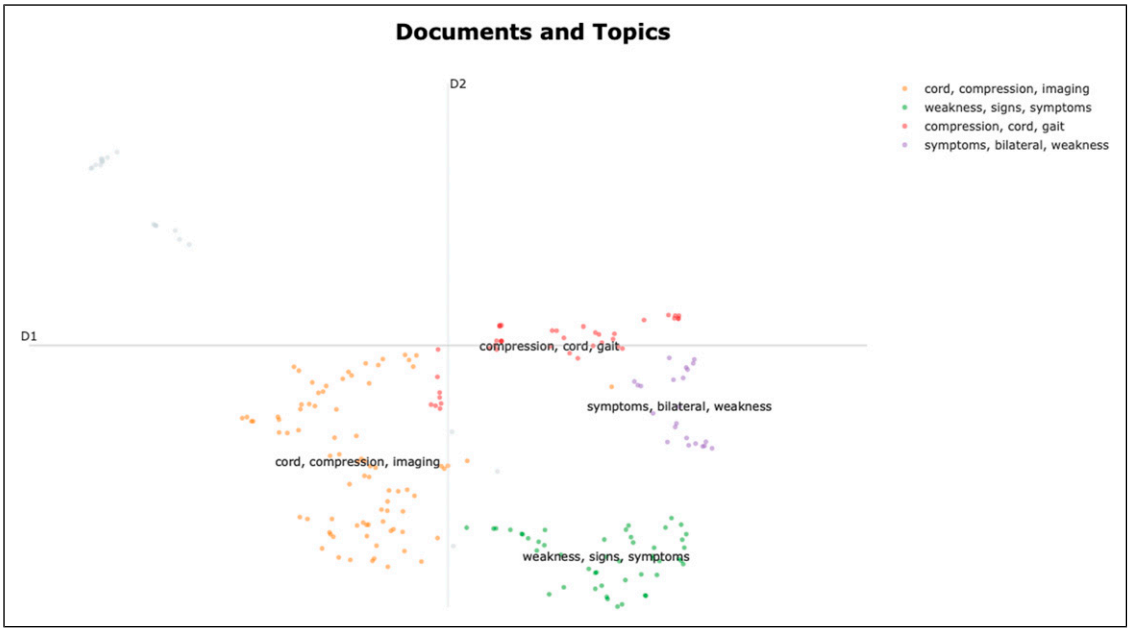

Figure 6. Clustering of the BERTopic model topics.

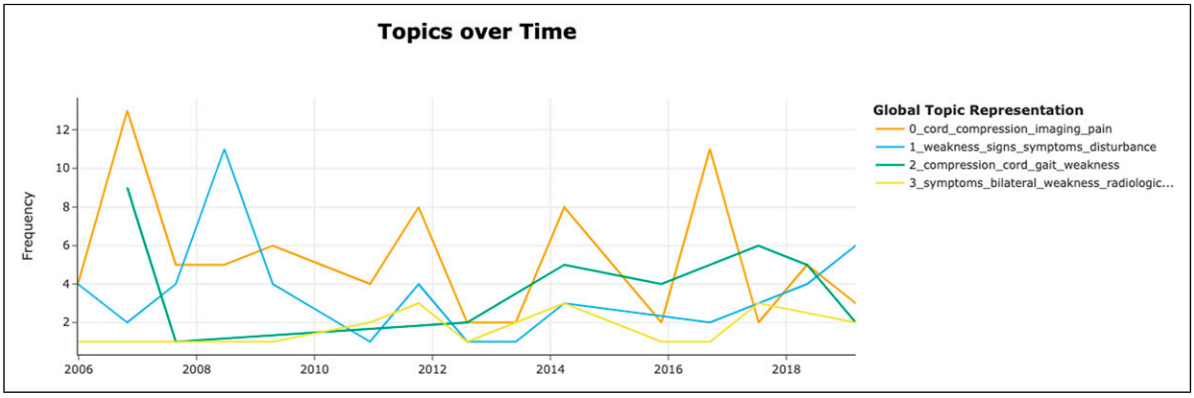

Figure 7. BERTopic model Topics over time.

non-traumatic, degenerative pathologies of the cervical spine causing spinal cord impairment secondary to mechanical compression, including cervical spondylotic myelopathy, OPLL, hypertrophy of the ligamentum flavum and degenerative disc disease.[3] This was selected as the best index term for the condition, and a formal definition was created.[1] Unfortunately, however, there is currently a lack of validated, reproducible, and standardized clinical, radiological and/or surgical diagnostic criteria of this hypernym. This absence includes the international classification of diseases, 11th

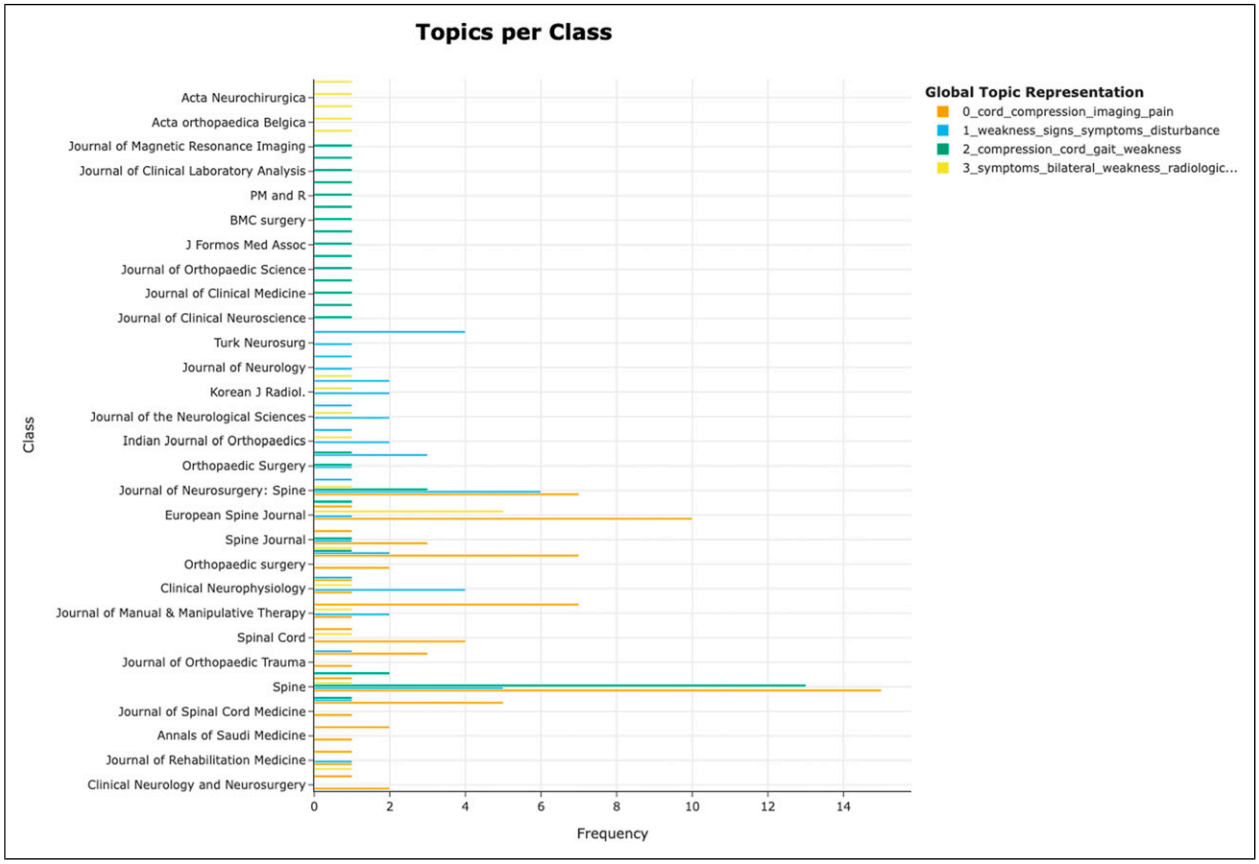

Figure 8. BERTopic model distribution in journals.

revision.[17] Therefore, recognizing and diagnosing DCM may pose a challenge to physicians.[28]

One of the reasons why DCM is often misdiagnosed is that it can present with a variable combination of clinical signs and symptoms. These clinical manifestations include but are not limited to neck pain or stiffness, arm paresthesias, decreased hand dexterity, upper or lower extremity weakness, gait instability, positive Hoffmann sign, increased upper and/or lower extremity deep tendon reflexes, and urinary, bowel and sexual dysfunction.[29-31] Notably, none of the aforementioned signs or symptoms is considered pathognomonic for the diagnosis of DCM. In addition, individuals with DCM may have atypical symptoms that have been associated with a particular level of spinal cord compression.[32] The incidence of these symptoms can be as high as 37%[32] and can further complicate the diagnostic process of DCM. Our analysis showed that motor impairment and fine-motor and sensory disturbance of the upper extremity were among the most common clinical criteria used to define DCM. These clinical symptoms reflect some of the items used in the mJOA score which is 1 of the accepted gold standards for evaluating functional impairment in patients with DCM. Interestingly, clinical signs (eg, positive Hoffmann or Babinski sign) were less commonly used to define DCM, despite representing an objective mean to assess for spinal cord compression. This finding is similar to the conclusions of a recent systematic review that suggested the most commonly used scales for assessing spinal cord function in DCM were more subjective and based on patient reports, including the JOA, mJOA, the Neck Disability Index, the Nurick tool and the Short Form 36 quality of life measure. In contrast, only 8% of the included studies assessed objective neurological findings.[29] In addition, the high prevalence of asymptomatic cases with incidentally found spinal canal stenosis and/or spinal cord compression poses another challenge in developing diagnostic criteria for DCM as these findings must be interpreted in the context of relevant clinical symptoms and signs.[33] Based on the results of this scoping review, the diagnostic algorithm of DCM may consider subjective assessments more than objective criteria.

The current scoping review offered significant insights into how DCM is diagnosed in the literature. It is evident that there was not a clear and consistent diagnostic algorithm used for identifying patients with DCM. Several approaches were used to analyze the data. The senior authors concluded that a quantitative analysis of all or some of the criteria would not be as powerful for providing contextual insights. Similarly, qualitative synthesis or mixed methods would be too time

intensive and introduce subjective biases. Therefore, NLP with topic modeling was selected since it is a contemporary method that provides novel insights compared to traditional analysis methods.

Themes that emerged from this analysis were that imaging with cord compression, and motor function of upper and lower extremities were weighted heavily in the diagnosis of DCM. Interestingly, clinical signs (eg, Hoffman's) as well as sensory features (eg, pain or paresthesias) were less important in diagnosing DCM, despite their reputed specificity or significance to patients, respectively. The interpretation of the emerging topics provides insight on what should be included in diagnostic criteria of DCM and creates interesting ideas. Based on topic analysis, the following concepts should be considered when developing DCM diagnostic criteria:

- weakness and motor signs are required for the diagnosis
- fine-motor and sensory disturbance of upper extremity is required for the diagnosis
- combination of imaging and clinical findings is required for the diagnosis
- disturbance to the patient from the symptoms is required for the diagnosis
- presence of clinical findings is required for the diagnosis
- description of "reinforcing" (or modifying) factors that can aid in the diagnosis in borderline cases, such as spinal instability, cord signal changes etc.
- description of imaging abnormality
- description of typical clinical features
- description of the range of objective criteria

The concept of "modifying factors" is particularly significant as the presence of these may help to reduce the number of missed patients when too much focus is placed on the classic presentation. These factors may also increase the weight of specific imaging findings pertinent to the condition.

The ultimate goal of this work was to summarize previously published definitions of DCM in order to later develop standardized diagnostic criteria for this condition. This endeavor aims to improve patient care by facilitating earlier diagnosis and treatment and providing a reference tool for primary care physicians, allied health professionals and other specialists that encounter DCM. In addition, diagnostic criteria will help to standardize future research studies, enhance the generalizability of results and increase external validity. To date, there has been no review that has identified commonly used inclusion criteria to screen for eligible research participants. Notably, there is tremendous variability with respect to what has been used as criteria for diagnosing DCM. Although identifying patients with DCM may be simple to some specialists, there is a significant proportion of patients who are diagnosed, and subsequently treated, in a delayed fashion. Given the annual admission rates of DCM have markedly increased over the last 2 decades, there is a pressing need to identify patients early in their disease course and refer them for definitive management.[3,34,35] Unfortunately, DCM is often misdiagnosed, particularly in milder forms, with a time between symptom onset and diagnosis often surpassing 3 years. This delay in diagnosis undoubtedly increases disease burden and results in incomplete postoperative recovery, impaired quality of life and life-long disability.[33]

In addition to the insights provided here, the development of DCM diagnostic criteria should consider additional factors.[36] First, the degree of cervical canal stenosis and cord compression do not always correlate with the severity of DCM. As such, diagnostic criteria must emphasize the need to interpret these imaging findings in the context of relevant signs and symptoms. Second, patients with milder symptoms and subtler signs of cord compression may not fully meet criteria for diagnosis of DCM and should be classified into categories such as possible, probable or conditional. Finally, another important consideration is that each criteria must be well-defined in order to reduce ambiguity and variability in interpretation. For example, in the literature the definition of the term 'weakness' varied from subjective, functional impairment to an objective loss of muscle strength in the Medical Research Council 0-5 scale.

Limitations

This study has several limitations. First, the authors aimed to investigate DCM definitions in only the last 2 decades. This was decided due to the large number of publications on this topic. Second, due to the volume of existing reports, each publication was screened by a single author. However, all reviewers who screened the reports were trained in a teach-back manner in order to assure accuracy and reliability. Finally, objective evaluation metrics of the topic modeling process are not available.[27] Furthermore, there is no ground truth for the topic modeling process. There is also no assurance that the produced topics will be "informative or useful from a human point of view." Topic modeling does, however, offer "interpretable, well represented and coherent groups of semantically similar documents". While human interpretation of topics by domain experts is the standard, these methods carry the inherent limitations of subjective interpretation. However, the analysis of the data by a multi-disciplinary group with considerable expertise in the subject mitigates these shortcomings.

Conclusion

The current scoping review summarizes commonly used criteria for diagnosing DCM based on literature published in the last 2 decades. There is currently no universally-accepted clinical definition of DCM. There is a pressing need to

standardize nomenclature and develop diagnostic criteria for DCM in order to facilitate timely diagnosis of this condition and implement appropriate management strategies. This study constitutes the first step of an effort to create a validated and widely accepted definition of DCM and diagnostic criteria. This study further exemplifies how topic modeling can provide a novel way to gain insights from the literature.

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Supplemental Material

Supplemental material for this article is available online.

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