Semiautomated Pipeline Effectively Assesses Severity and Monitor Disease Progression in Compressed Spinal Cord of Degenerative Cervical Myelopathy Patients

Fauziyya Muhammad, MD, PhD*, Kenneth A. Weber II, DC, PhD‡, Sandrine Bédard, MSc§, Grace Haynes, BS||, Zachary A. Smith, MD*

*Department of Neurosurgery, University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma, USA; ‡Department of Anesthesiology, Perioperative and Pain Medicine, Stanford School of Medicine, Palo Alto, California, USA; §NeuroPoly Lab, Institute of Biomedical Engineering, Polytechnique Montreal, Montreal, Canada; ||Stephenson School of Biomedical Engineering, University of Oklahoma, Norman, Oklahoma, USA

Correspondence: Fauziyya Muhammad, MD, PhD, Department of Neurosurgery, University of Oklahoma Health Sciences Center, 1000 N Lincoln Blvd, Suite 4000, Oklahoma City, OK 73104, USA. Email: Fauziyya-muhammad@ouhsc.edu

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BACKGROUND AND OBJECTIVES: Degenerative cervical myelopathy (DCM) is a progressive and disabling condition resulting from chronic compression of the spinal cord, leading to functional impairments that can severely affect quality of life. Traditional methods for assessing spinal cord injury and morphometrics rely on subjective visualization of contrast changes and manual segmentation, which are nonstandardized, time-consuming, and inconsistent across patients. This variability limits understanding of DCM pathology and hampers timely clinical intervention.

METHODS: We introduce a semiautomated pipeline using the Spinal Cord Toolbox, an open-source platform that uses advanced algorithms, including optimization and computational efficiency algorithms, support vector machine, and convolutional neural networks, to streamline the assessment of spinal cord shape, microstructural changes, and gray and white matter integrity. By integrating spinal cord segmentation, anatomical labeling, and registration to a standardized template, the pipeline extracts normalized morphometric measures, providing efficient and reliable analysis of spinal cord pathology in DCM.

RESULTS: We extracted normalized spinal cord morphometrics, including cross-sectional area (CSA), anterior-posterior diameter, right-left diameter, eccentricity, solidity, gray matter CSA, white matter CSA, and regional and tract-based magnetization transfer ratio measures. Our analysis demonstrates that DCM patients exhibit significant reductions in these morphometrics compared with healthy controls, even in regions without visible compression. Furthermore, CSA reductions across the spinal cord highlight areas of severe compression, including at the intervertebral disks, which may not be apparent on standard imaging.

CONCLUSION: These quantitative measures give clinicians easily interpretable data on the extent of spinal cord injury, even in regions without obvious compression. This enables a comprehensive understanding of DCM pathophysiology. By eliminating the subjectivity of manual segmentation and accounting for intersubject and intrasubject variability, this approach supports consistent cross-subject comparisons and is poised to reshape how clinicians assess and manage DCM.

KEY WORDS: Degenerative cervical myelopathy, Gray matter, MRI, Magnetization transfer, Spinal cord toolbox, T2 weighted, White matter tracts

Degenerative cervical myelopathy (DCM) is the most common cause of spinal cord disorder in individuals aged older than 50 years leading to significant neurological impairment and reduced quality of life.[1,2] The complex pathogenesis of DCM, driven by chronic spinal cord compression from multifactorial causes such as disk herniation and osteophyte formation, results in a highly variable clinical presentation.[2] Parameters such as spinal cord shape, morphometrics, and

ABBREVIATIONS: CSA, cross-sectional area; **DCM,** degenerative cervical myelopathy; **GM,** gray matter; **HC,** healthy controls; **MT,** magnetization transfer; **MTR,** magnetization transfer ratio; **QC,** quality control; **SCT,** Spinal Cord Toolbox; **WM,** white matter.

Supplemental digital content is available for this article at neurosurgerypractice-online.com.

CODE:
https://github.com/Mfauziyya/DCM_Neurosurgery_Practice

CODE FUNCTIONALITY:
OU Spine: https://github.com/Mfauziyya/DCM_Neurosurgery_Practice/tree/main/Scripts

DATASET:
https://github.com/Mfauziyya/DCM_Neurosurgery_Practice/tree/main/Example%20data

KEY RESULTS:

Image Sequence	Function	Algorithm	Measure	HC (15)	DCM (30)
T2 weighted	sct_deepseg_sc	CNN and OptiC			
	sct_label_vertebrae	OptiC			
	sct_register_to_template	Straightening algorithm and affine transformation			
		sct_process_segmentation	CSA	79.34 (6.52)	64.72 (9.70)
			AP	7.87 (0.41)	6.90 (0.78)
			RL	12.89 (0.83)	12.02 (0.79)
T2 Star	sct_deepseg_gm	CNN			
	sct_register_template	Several algorithms for spinal cord straightening			
		sct_process_segmentation	GM CSA	15 (1.6)	12 (3.1)
			WM CSA	115 (13.4)	90 (26.4)
MT	sct_register_multimodal	MeanSquare metric, different Algorithm for transformation			
	sct_extract_metric	Maximum a posteriori	MTR	36.46 (3.2)	33.52 (3.65)

**All measures presented are extracted at C3 level. MT, magnetization transfer; MTR, magnetization transfer ratio; WM, white matter; GM, gray matter; CSA, cross sectional area; CNN, convolutional neural networks; RL, right-left (transverse) diameter; AP, anterior-posterior diameter; HC, healthy control; DCM, degenerative cervical myelopathy.

hyperintensity are recognized as key biological markers because they show association with clinical symptoms of DCM.[1,3,4]

Despite growing recognition of spinal cord morphometrics such as cross-sectional area (CSA), shape alterations, and microstructural integrity as valuable biomarkers,[5-7] the widespread adoption of these measures in clinical practice has been limited. Manual segmentation of spinal cord MRI is labor-intensive, prone to variability, and particularly challenging in regions of compression, creating barriers to clinical translation.[8,9] To address these challenges, we designed an analysis pipeline based on the Spinal Cord Toolbox (SCT), to streamline the extraction of key morphometric data from spinal cords of patients with DCM. This pipeline is a game-changing solution that can provide clinicians with standardized, quantitative metrics that are easy to interpret and clinically actionable, even in complex compression regions of the spinal cord.[1,10] We incorporate a Batch-processing command that enables reliable and rapid extraction of spinal cord morphometrics across multiple subjects.[10] Evidence from Muhammad et al has demonstrated the efficacy of this automated pipeline in extracting morphometric data from compressed spinal cords in 36 DCM patients, whereas Haynes et al further validated its performance in generating clinically relevant white matter (WM) injury metrics to elucidate the severity of DCM.[1,4]

Our study leverages this pipeline to demonstrate how morphometric analysis can enhance clinical decision making in DCM, facilitating early diagnosis, improved monitoring, and prognosis of DCM.

METHODS

Data Set

Our spine data are a prospective study initiated in 2021, focused on longitudinal data collection in DCM patients. Using a convenience

TABLE. Inclusion and Exclusion Criteria for OU Spine Study
Criteria for patients with DCM
Inclusion: Eligible DCM patients must have a clear evidence of cervical spinal cord compression on T2-weighted MRI scan. In addition, they are required to exhibit at least one clinical sign of myelopathy, which include
a. demonstrate abnormally increased reflexes (Hyper-reflexia)
b. demonstrate a positive Hoffman test
c. difficulties with hand coordination
d. problems with walking
e. a noticeable motor weakness
Exclusion
a. Patients will not be included if they are younger than 30 years or older than 80 years
b. The history of any spine surgery also renders a patient ineligible
c. If a patient has three or more significant health conditions, for example, uncontrolled diabetes or hypertension Individuals diagnosed with neurodegenerative conditions (such as Parkinson disease, Alzheimer disease, ALS, or MS)
d. Patients with active systemic rheumatological disorders. patients who present with isolated radiculopathy without signs of myelopathy
e. A past or current history of active peripheral neuropathy, epilepsy
f. Patients currently pregnant or breastfeeding will be excluded
g. Any individual who cannot complete the study procedures due to a medical condition requires immediate surgical decompression
h. DCM patients with urgent need for surgical decompression
i. Participants who shows asymptomatic spinal cord compression (defined by a normal mJOA score of 18 despite radiological evidence)
Criteria for controls
Inclusion
a. Participants must be between the ages of 30 and 80 years
b. Participant must display no clinical signs of neurological impairment, as evidenced by a Nurick grade of 0 and a mJOA score of 18. The individual may still be considered eligible if minor sphincter dysfunction is attributable solely to nonspinal conditions (such as prostate or other genitourinary problems)
Exclusion
a. Control participants will be excluded if they have been diagnosed with any neurodegenerative disorder (for example, ALS or MS)
b. Participants who are currently pregnant or breastfeeding are not eligible
c. Participants with active systemic rheumatological condition, active peripheral or vascular neuropathy, and/or >3 major comorbid states will be excluded
d. Participants with any history of spinal surgery at any level will be excluded
e. Participants who face any medical issues that would prevent the completion of study procedures. h. Participants with current spinal conditions, symptoms of neck pain, or neurological deficit

ALS, amyotrophic lateral sclerosis; DCM, degenerative cervical myelopathy; mJOA, modified Japanese Orthopedic Association; MS, multiple sclerosis.
All study participants must also be capable of providing legally written informed consent.

sampling method, we enrolled all DCM patients from our Adult Neurosurgery clinic who meant the inclusion and exclusion criteria outlined in (Table). This data set is part of an ongoing effort to identify and validate spinal cord biomarkers that can inform clinical management. The study received ethical approval from the Internal Review Board, and written informed consent was obtained from all participants. A flow chart outlining the recruitment process is shown in the **Supplemental Digital Content 1** (http://links.lww.com/NS9/A42).

The data set includes structural and quantitative MRI spine data and clinical assessments, with repeated imaging over time to track the progression of spinal cord degeneration in nonsurgically treated patients. This allows for the identification of key imaging biomarkers that may correlate with symptom severity and guide clinical interventions. Because data collection and studies are ongoing, only a sample of the data is included in the GitHub repository. Deidentified spine data set is available from the senior author on reasonable request.

MRI Acquisition

To standardize image acquisition and ensure high-quality data across multiple MRI systems, we used the Spine Generic Protocol, a publicly available standard operational procedure tailored for T2-weighted, T2-star, and magnetization transfer (MT) imaging.[11] This protocol supports acquisition on 3-T scanners from Siemens, Philips, and GE, ensuring broad applicability in clinical settings.[11] The protocol has been validated on a cohort of 260 healthy control subjects, demonstrating its suitability for imaging diverse populations.[10-12]

Statistical Methods

The analysis was conducted on a MacOS Catalina system equipped with a 3.8 GHz 8-core Intel i7 processor and 64 GB of RAM (Apple Inc.). The SCT (Institute of Biomedical Engineering, Polytechnique Montreal) was installed following the user-friendly instructions available on the Spinal Cord Toolbox website. The SCT-batch pipeline is optimized for efficiency and can be executed on standard consumer-grade hardware systems. Detailed hardware we used is provided in **Supplemental Digital Content 1** (http://links.lww.com/NS9/A42) to facilitate replication

Statistical tests were performed using GraphPad Prism Version 10.1.2 (GraphPad Software) and Python Library Version 3.9 (Python Software foundation). All continuous variables, including demographic of healthy controls (HC) and DCM, were assessed for normality using the D'Agostino and Pearson test. For normally distributed data, two-sample *t*-tests were used for two variables (between group comparison of gray matter (GM) and WM CSA, Spinal cord CSA[1]) between groups. One-way analysis of variance was used for comparisons involving more than two groups. For non-normally distributed MRI metrics, Wilcoxon rank-sum test was used for group comparison (T2-CSA, magnetization transfer ratio [MTR]) between HC and DCM. In addition, the Kruskal-Wallis test was used for regional MTR comparisons involving more than two variables.

Code Availability

All processing scrips and codes, including sample data set, are available at https://github.com/Mfauziyya/DCM_Neurosurgery_Practice.

Semiautomated Analysis Pipeline for Clinical Use

To address the challenges of manual segmentation, particularly in compressed spinal cord regions, we implemented a semiautomated pipeline using the SCT designed to simplify and accelerate the extraction of clinically relevant morphometric measures.[13,14] This pipeline integrates advanced deep learning algorithms for spinal cord detection and segmentation to enhance the efficiency, accuracy, and reproducibility of spinal cord segmentation and morphometric extraction that is easy interpretation with reduce burden on clinicians. Major steps included in this pipeline include:

Segmentation

Accurate segmentation of the spinal cord is critical for extracting morphometric data such as CSA, which is a key biomarker for spinal cord atrophy.[15,16] Our pipeline uses the SCT DeepSeg algorithm, a deep learning–based tool that applies optimization and computational efficiency algorithms and convolutional neural networks to automatically detect and segments the spinal cord from surrounding tissues (Figure 1).[17,18] In regions of compression, automatic segmentation may be less

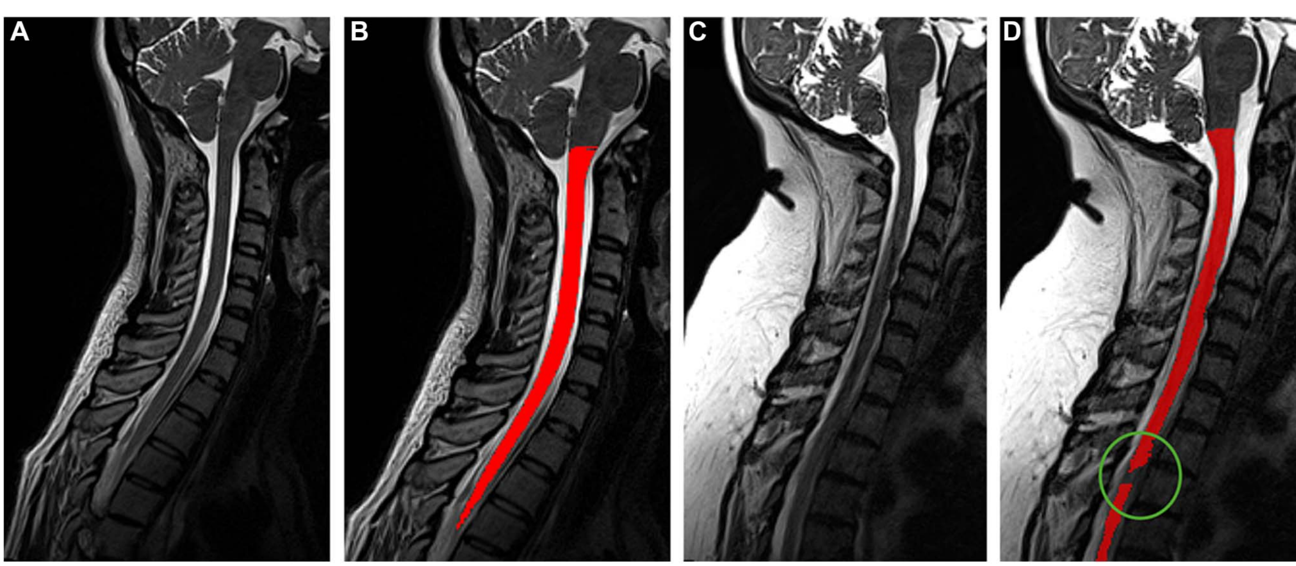

FIGURE 1. *T2-weighted MR images showing automatic spinal cord segmentation (in red) for precise delineation of cord boundaries for further processing.* **A** *and* **B**, *show healthy control, whereas the* **C** *and* **D**, *shows segmentation results from a degenerative cervical myelopathy patient. The green circle highlights a segmentation error that requires manual correction, identified after reviewing the data in the quality control interface.*

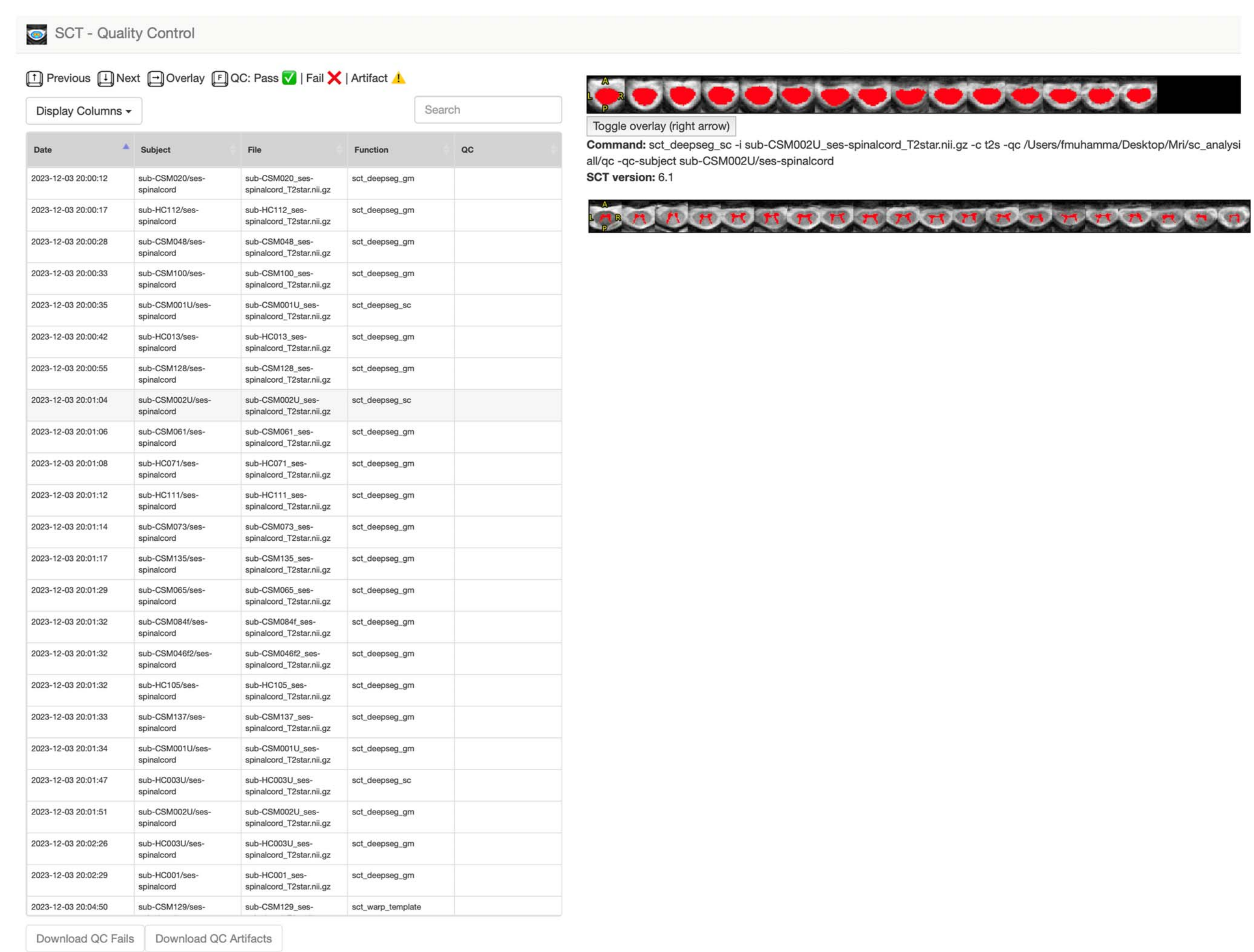

FIGURE 2. *Quality control web-based interface for reviewing automatic processing. Overview of all subject data listed to identify processing errors. SCT command parameters used for each processing step. Automated spinal cord segmentation overlaid on the native image. Gray matter segmentation overlaid on a T2*-weighted image. SCT, Spinal Cord Toolbox.*

reliable because of reduced contrast, but the SCT quality control (QC) interface allows clinicians to manually adjust segmentations where necessary (Figure 2).[14] This ensures that even in challenging regions, segmentation is accurate, enabling reliable downstream analyses.

Vertebral Labeling

The SCT pipeline includes automated vertebral labeling using a deep learning algorithm, which identifies the vertebral levels within the spinal cord (Figure 3A).[13,19] This is essential for aligning MRI images with the PAM50 (Polytechnique Montreal, Aix-Marseille Université and Montreal Neurological Institute) template, a standardized anatomical template space that facilitates cross-subject comparisons.[20] In cases of vertebral height reduction or disk collapse, which are common in DCM patients, the automatic algorithm may fail. In these cases, we use a semiautomated approach by manually labeling key vertebrae such as C2 and C3 to ensure accurate labeling and registration.[21]

Manual adjustments were required in 25% of DCM patients, especially at the levels of compression, compared with 3% of HC. All manual corrections were performed by FM and GH, and the adjustments were visually inspected in the SCT QC report to ensure consistency.

Registration to PAM50 Template

To enable the comparison of spinal cord measures across patients and to standardize morphometric metrics, the SCT pipeline registers individual spinal cord images to the PAM50 template (Figure 3B), a multimodal, unbiased reference space.[20] The PAM50 template includes anatomical information from C1 to L2 vertebral levels, allowing clinicians to assess changes along the entire spinal cord.[10] By normalizing patient data to this template, we can derive consistent measures, such as CSA and spinal cord shape metrics, across multiple time points or patients. This step ensures that clinicians can compare spinal cord morphology and microstructural integrity across subjects, regardless of individual anatomical variability.

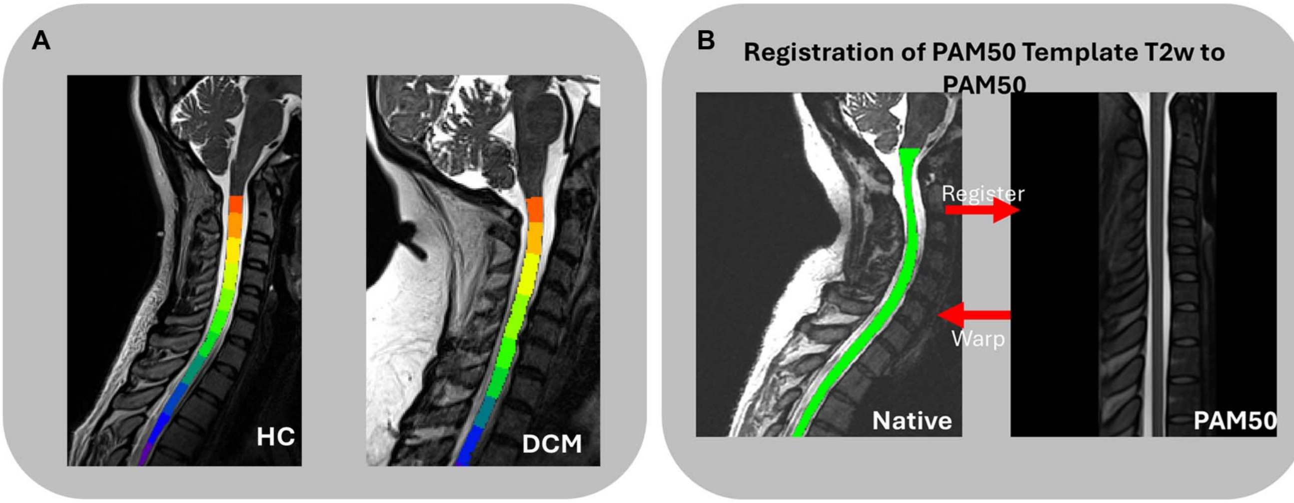

FIGURE 3. *Cervical spinal cord label in a HC and a patient with DCM.* **A**, *The heatmap illustrates the segmentation of different spinal cord segments.* **B**, *Registration of the native T2-weighted images to PAM50 template. The spinal cord is first registered to the template to normalize the metric for consistent anatomical comparison across subject (red arrows) and then warped to the native image for subject-specific measures. DCM, degenerative cervical myelopathy; HC, healthy control.*

Quantitative Measures from Magnetization Transfer Imaging (MT)

MT imaging is a valuable tool for assessing WM integrity, providing quantitative measures such as the MTR.[22] Our pipeline automates the registration of MT-on and MT-off images to compute MTR, offering insights into myelin integrity and WM damage in specific spinal cord regions and tracts (Figure 4). This is particularly important in DCM, where microstructural changes in WM tracts, such as the corticospinal tract, can directly correlate with the severity of DCM and motor dysfunction.[4,23,24]

By providing tract-specific MTR measures, the SCT pipeline allows clinicians to assess the extent of WM damage and track changes over time, informing both diagnosis and treatment strategies.

Gray Matter Mapping With T2-Star Imaging

The SCT pipeline leverages deep learning architecture model for spinal cord GM segmentation.[25] Using T2-star imaging which provides a high contrast difference between GM and WM. These contrast differences allow for precise segmentation of GM, enabling detailed morphometric analysis of the GM horns (Figure 5A and 5B), thus providing a deeper understanding of disease pathology.[26]

Compute Compression Function

The *sct_compute* compression function is particularly useful for assessing the severity of compression in DCM patients, providing clinicians with objective data to guide treatment planning. This function computes normalized metrics at the site of compression, comparing compressed levels to noncompressed regions above and below the injury (Figure 5C).[27] By integrating these compression metrics with clinical symptoms, clinicians can make more informed decisions about the extent of compression that guide timing of surgical interventions.[1] and the potential benefits of decompression surgery.

RESULTS

The SCT pipeline successfully segmented the spinal cord and extraction of several key morphometric and microstructural metrics that are directly relevant to clinical practice were obtained.[1,4]

Shape Morphometrics from T2-Weighted Image

This includes *CSA*, a key metric for assessing spinal cord atrophy, which correlates with the severity of DCM (Figure 6). By normalizing CSA to noncompressed levels, clinicians can better assess the impact of compression on spinal cord structural integrity. A reduction in CSA has been shown to elucidate the extent and progression of spinal cord atrophy in conditions such as multiple sclerosis.[7] Many studies show that CSA is a clinically useful measure that provides insights into the spinal cord's overall health. In our study, we show a clear reduction in normalized CSA at all cervical vertebral levels in DCM patients compared with HC (Figure 6B). The CSA is reduced across all vertebral levels in the DCM group, with more pronounced reductions at the intervertebral disk levels Figure 6B. In conservatively treated DCM patients, we observed a progressive decrease in CSA at the 6-month follow-up relative to baseline measures Figure 6C. This finding suggests that spinal cord atrophy can worsen over time without surgical intervention.[1] Furthermore, we have shown a strong association between CSA measurement and clinical symptoms.[1] The *Anterior-Posterior and Transverse Diameters* provide valuable insights into the degree of spinal cord stenosis. The AP diameter is particularly useful in identifying the severity of spinal cord compression, while the transverse diameter (RL)

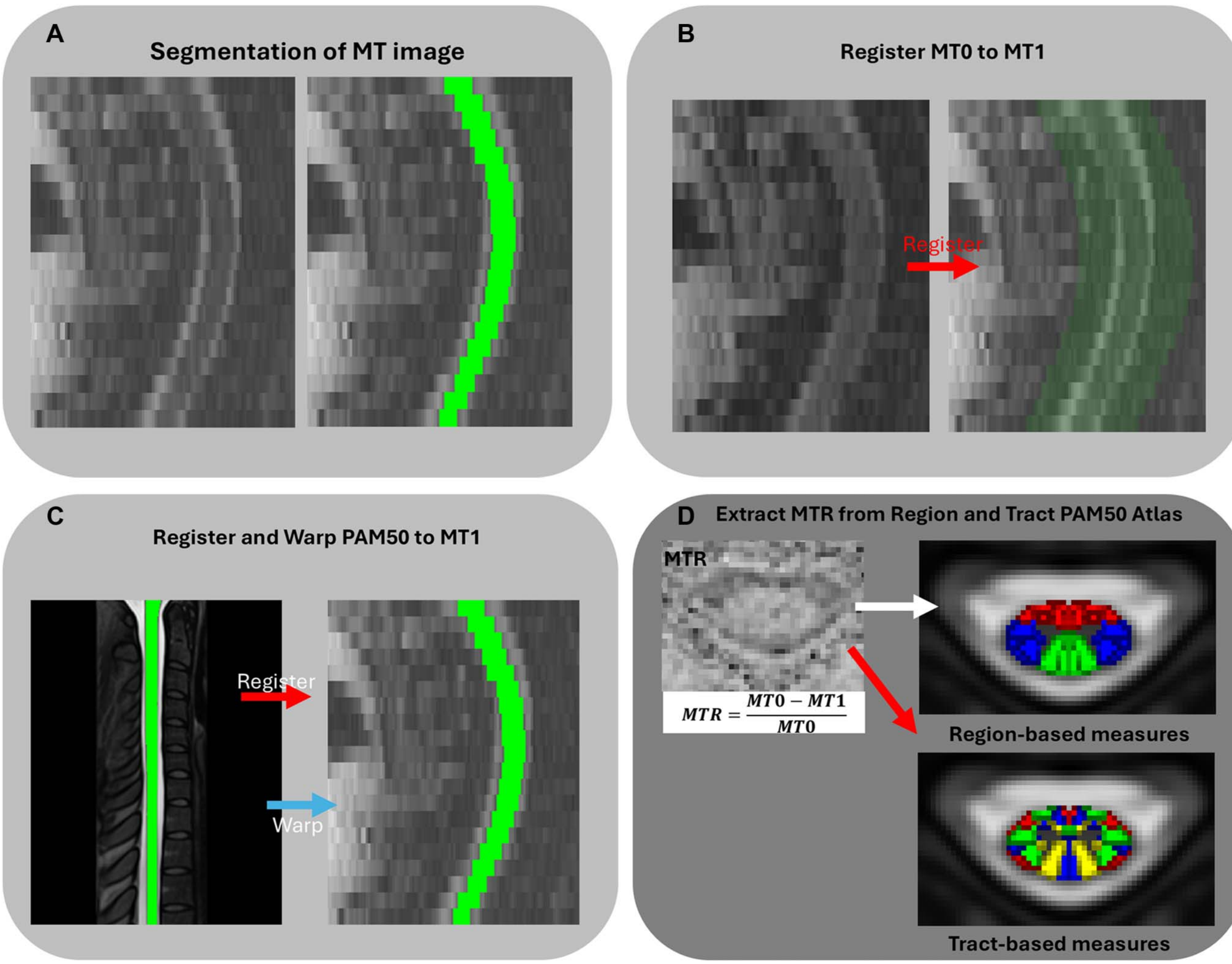

FIGURE 4. *Detailed workflow of spinal cord segmentation, registration, and extraction of MTR.* **A**, *The spinal cord is automatically segmented (green outline) from the MT image.* **B**, *Coregistration of MT-off (MT0) to MT-on (MT1) to ensure accurate alignment of anatomical structures. The red arrow indicates the registration process, which improves the consistency of MTR calculation.* **C**, *Registration and Warping of PAM50 to MT1: The PAM50 template is first registered to the native MT-on image (red arrow) and then warped (blue arrow) to match the subject's spinal cord. This step facilitates the extraction of region-based and tract-based measures by aligning subject-specific data with a standardized template.* **D**, *Extraction of MTR from Region and Tract PAM50 Atlas: MTR is calculated using the MTR formula and extracted from regions of interest. MT, magnetization transfer; MTR, magnetization transfer ratio.*

provides information about the extent of lateral (side-to-side) involvement and potential foraminal narrowing. Together, these metrics offer a quantitative measure of localized compression severity. In our research, we have demonstrated that AP diameter measurements can effectively identify the extent of spinal cord compression, even in patients with asymptomatic spinal cord compression.[3] The *Compression metric (*maximum spinal cord compression*)* is a computed normalized morphometrics at the region of maximum compression.[1] In other studies, maximum spinal cord compression has been shown to be a reliable biomarker of spinal cord injury, correlating with the severity of injury and neurological impairments. It has also been used to assess the outcomes of acute traumatic spinal cord injuries.

Magnetization Transfer Ratio (MTR)

It provides a quantitative measure of WM integrity, providing clinicians critical information about the severity of DCM[4,28] and helping to inform prognosis of DCM.[24] MTR has also become a valuable clinical technique for assessing WM integrity in multiple sclerosis. Gray Matter Cross-Sectional Area (CSA): T2*-based gray matter mapping provides insights into damage to motor and sensory pathways by assessing the morphological changes in the

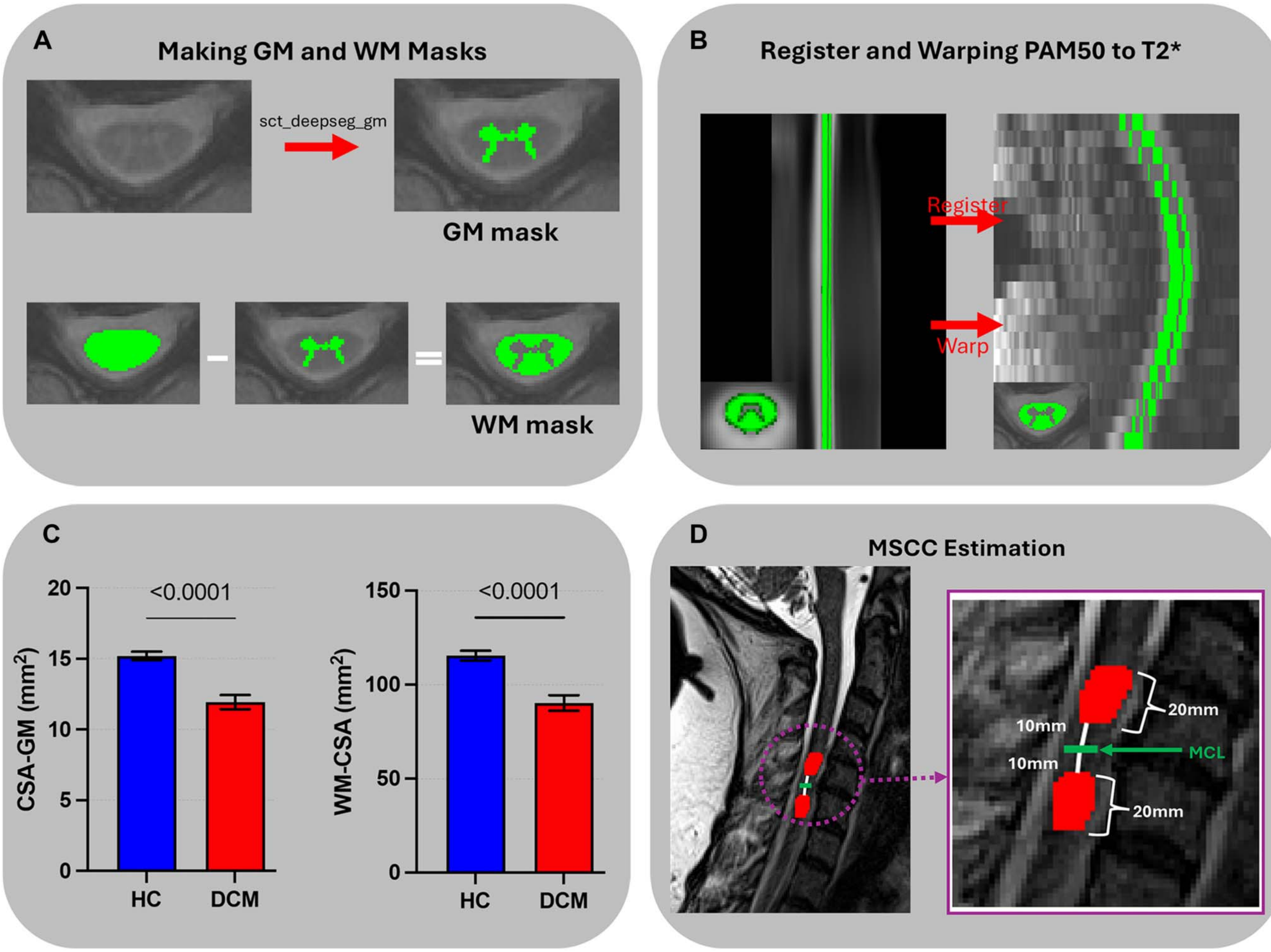

FIGURE 5. A and B, *Overview of spinal cord gray matter and WM morphometrics T2-star image.* A, *Segmentation of the spinal cord in a T2-star image and result of applying the sct_deepseg_gm algorithm.* B, *Registration and warping of PAM50 to T2* image with PAM50 template space. These steps enable GM or WM morphometric analysis across subjects.* C, *Bar graphs show summary data of normalized GM CSA and WM CSA between HC (n = 22) and degenerative cervical myelopathy (n = 35) extracted at C3 level. MSCC Estimation (T2-weighted image): The morphometrics at the site of MCL is calculated from T2-weighted images. The left image highlights the location of compression (red) along the spinal cord. The zoomed-in panel (right) shows how measurements are taken: 10-mm above and below the point of maximum compression, with an additional 20-mm measurement along the MCL for intrasubject normalization analysis of the compressed region as described by Bedard et al 2024.[27] CSA, cross-sectional area; GM, gray matter; MCL, maximum compression level; MSCC, maximum spinal cord compression; WM, white matter.*

GM horns (Cloney et al). GM atrophy above the stenotic region has been associated with clinical dysfunctions in DCM.[29] Furthermore, changes in WM-GM signal intensity ratio derived from T2* imaging have been shown to be a better biomarker for spinal cord WM injury.[30]

Furthermore, MTR measures offer increased sensitivity in detecting microstructural damage beyond the visible site of spinal cord compression (accompany paper, currently under review). This provides a more comprehensive view of the extent of spinal cord injury particularly important for understanding the full impact of DCM that may help optimize patient treatment.

Correlation of Spinal Cord Measures With Clinical Symptoms

We have demonstrated a strong association of these measures with clinical severity of DCM such as CSA significantly associated with dexterity dysfunctions scores[1] and MTR (tract and region-based measures) associated with DCM severity (modified Japanese Orthopedic Association).[4]

DISCUSSION

This study successfully establishes and validated a semi-automated analysis or the segmentation and morphometric

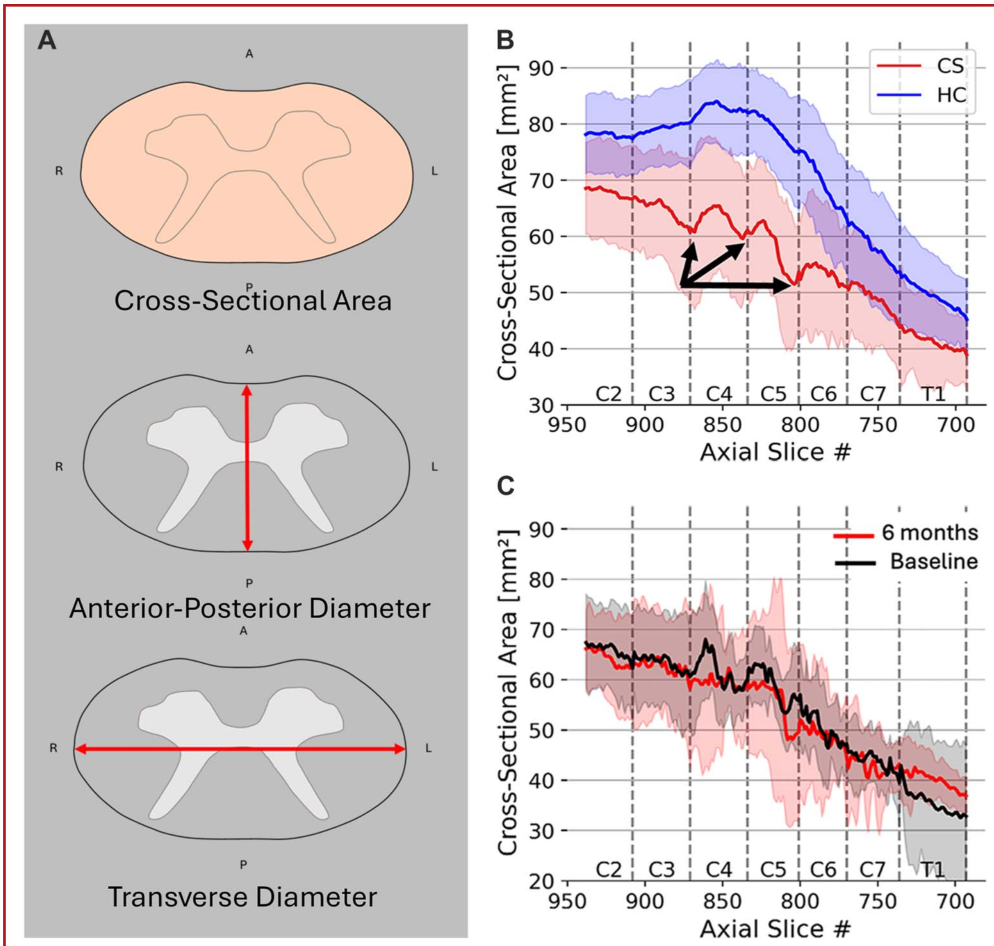

FIGURE 6. **A**, *Illustrations of the morphometric measures extracted during this pipeline. These illustrations are similar to description from the Spinal Cord Toolbox website.*[21] **B**, *Comparison of normalized cervical spinal cord CSA in DCM (red, n = 36) vs HC (blue, n = 31), showing reduced CSA at all vertebral levels, most notably at the intervertebral disks (black arrows).* **C**, *Longitudinal CSA measurements in conservatively treated DCM patients (n = 7) show further CSA reduction at 6-month follow-up (red) compared with baseline (black).* **B** *and* **C**, *are reprinted from The Spine Journal, Vol 24(11), F. Muhammad et al, cervical spinal cord morphometrics in degenerative cervical myelopathy: quantification using semiautomated normalized technique and correlation with neurological dysfunctions, Pages 2045-2057, Copyright 2024, with permission from Elsevier. CSA, cross-sectional area; DCM, degenerative cervical myelopathy.*

evaluation of the compressed cervical spinal cord in patients with DCM. We designed these analysis code and pipeline leveraging the SCT algorithms to accurately measure spinal cord CSA, AP and transverse diameter, eccentricity based on the compression ratio, and solidity from an isotropic T2-weighted MRI scan. In addition, our pipeline can estimate GM volume, GM, and WM CSA, from T2-star scans, while assessing WM integrity using MT images.[14] Validation of the SCT algorithms was achieved through training models and comparing automated measures with manually drawn assessments as ground truth to demonstrate accuracy and reliability. The implementation of batch processing significantly reduces analysis time for multiple patient scans. Furthermore, the integration of the PAM50 Atlas facilitates normalized measures for intersubject comparison.[10,20] The QC interface ensures the reliability and accuracy of the measurements. Notably, our analysis pipeline demonstrates the application across spectrum, of DCM severity.[4]

The morphometric measures obtained from this pipeline are clinically meaningful.[1,3,4] Specifically, parameters such as CSA and AP diameter significantly correlated with key deficits in DCM including loss of dexterity and grip strength. In addition, changes in MTR measures effectively reflect the severity and prognosis of DCM.[4,24] Furthermore, our pipeline provides clinically relevant visualization of spinal cord compression and measures highlighting changes through the cervical spinal cord and pinpointing regions of disk compression.[1] Parameters indicates that the pipeline meets this objective, providing comprehensive insights into spinal cord atrophy and integrity alterations because of chronic compression in DCM.[31,32] These findings indicate that the pipeline not only quantifies spinal cord alterations but offers valuable insights into the functional impairments in DCM.

The generalizability of our pipeline may be influenced by factors such as differences in MRI scanners, image quality, user experience with coding, and interactions with the graphical user interface and terminal. To enhance robustness and adaptability across various clinical scenarios, future endeavors will focus on fully automating the pipeline to account for all imaging types and different spinal conditions. In addition, work is already underway to improve segmentation accuracy in severely compressed regions and reduce the need for manual corrections, thereby minimizing user-defined bias.[31-33] Future studies will incorporate advanced metrics for longitudinal tracking of spinal cord morphometrics to enable precise monitoring of changes in patients undergoing conservative treatment.[1] Expanding the pipeline's validation to include multisite patients' data sets and diverse imaging modalities will further strengthen its reliability and applicability. These efforts are key to establishing the pipeline's effectiveness and ensure its widespread utility in routine clinical practice.

A limitation of our study is that manual correction of segmentation may introduce user-defined bias. However, the embedded QC interface allows for adjustments, and recent iterations of the SCT segmentation algorithms, including the newly develop contrast-agnostic and SCIseg, have significantly improved the accuracy of spinal cord segmentation.[31,32,34] In addition, our analysis pipeline has been applied to a single-site data set, which may limit its generalizability. We are currently piloting our analysis code on data collected from another site University of Texas Southwestern), and the results from a larger series will be available in the future. WM tract–specific measures in severely compressed regions may be prone to error because of poor tract delineation, potentially influenced by partial volume effects and anatomical distortion. Although our pipeline is robust, these distortions may affect the interpretation of results in severely affected areas. However, the pipeline remains sensitive in detecting track changes above and below the region of compression, providing more reliable insights in those areas.

CONCLUSION

In conclusion, our SCT-based analysis pipeline provides a robust, scalable, and clinically relevant tool for the assessment of DCM. By automating the segmentation, labeling, and registration of spinal cord images, the pipeline generates standardized and reproducible morphometric measures that are directly translatable to clinical practice. These metrics allow clinicians to quantify spinal cord damage, assess disease progression, and tailor treatment strategies to individual patients. The integration of MT and T2* further enhances the pipeline's ability to assess both white and gray matter integrity, offering valuable insights into the microstructural changes that accompany.

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Disclosures

The authors have no personal, financial, or institutional interest in any of the drugs, materials, or devices described in this article.

REFERENCES

1. Muhammad F, Weber KA, Bédard S, et al. Cervical spinal cord morphometrics in degenerative cervical myelopathy: quantification using semi-automated normalized technique and correlation with neurological dysfunctions. *Spine J.* 2024;24(11): 2024-2025.
2. Tetreault L, Kalsi-Ryan S, Benjamin D, et al. Degenerative cervical myelopathy: a practical approach to diagnosis. *Global Spine J.* 2022;12(8):1881-1893.
3. Hameed S, Muhammad F, Haynes G, Smith L, Khan AF, Smith ZA. Early neurological changes in aging cervical spine: insights from PROMIS mobility assessment. *Geroscience.* 2024;46(3):3123-3134.
4. Haynes G, Muhammad F, Weber KA, et al. Tract-specific magnetization transfer ratio provides insights into the severity of degenerative cervical myelopathy. *Spinal Cord.* 2024;62(12):700-707.
5. Al-Tameemi HN, Hassoun HK, Mohammed IQ, Allebban Z. MRI assessment of cervical spinal cord cross-sectional area in patients with multiple sclerosis. *J Neurosci Rural Pract.* 2023;14(4):660-666.
6. Bernitsas E, Bao F, Seraji-Bozorgzad N, et al. Spinal cord atrophy in multiple sclerosis and relationship with disability across clinical phenotypes. *Mult Scler Relat Disord.* 2015;4(1):47-51.
7. Mina Y, Azodi S, Dubuche T, et al. Cervical and thoracic cord atrophy in multiple sclerosis phenotypes: quantification and correlation with clinical disability. *Neuroimage Clin.* 2021;30:102680.
8. Liao CC, Ting HW, Xiao F. Atlas-free cervical spinal cord segmentation on midsagittal T2-weighted magnetic resonance images. *J Healthc Eng.* 2017;2017: 8691505.
9. Prados F, Ashburner J, Blaiotta C, et al. Spinal cord grey matter segmentation challenge. *Neuroimage.* 2017;152:312–329.
10. Valošek J, Bédard S, Keřkovský M, Rohan T, Cohen-Adad J. A database of the healthy human spinal cord morphometry in the PAM50 template space. *Imaging Neurosci.* 2024;2:1-15.
11. Cohen-Adad J, Alonso-Ortiz E, Abramovic M, et al. Generic acquisition protocol for quantitative MRI of the spinal cord. *Nat Protoc.* 2021;16(10):4611-4632.
12. Cohen-Adad J, Alonso-Ortiz E, Abramovic M, et al. Open-access quantitative MRI data of the spinal cord and reproducibility across participants, sites and manufacturers. *Sci Data.* 2021;8(1):219.
13. De Leener B, Lévy S, Dupont SM, et al. SCT: spinal Cord Toolbox, an open-source software for processing spinal cord MRI data. *Neuroimage.* 2017;145(Pt A):24-43.
14. Valošek J, Cohen-Adad J. Reproducible spinal cord quantitative MRI analysis with the spinal cord toolbox. *Magn Reson Med Sci.* 2024;23(3):307-315.
15. Dupont SM, De Leener B, Taso M, et al. Fully-integrated framework for the segmentation and registration of the spinal cord white and gray matter. *Neuroimage.* 2017;150:358–372.
16. De Leener B, Taso M, Cohen-Adad J, Callot V. Segmentation of the human spinal cord. *MAGMA.* 2016;29(2):125-153.
17. Paugam F, Lefeuvre J, Perone CS, et al. Open-source pipeline for multi-class segmentation of the spinal cord with deep learning. *Magn Reson Imaging.* 2019;64: 21–27.
18. Gros C, De Leener B, Badji A, et al. Automatic segmentation of the spinal cord and intramedullary multiple sclerosis lesions with convolutional neural networks. *Neuroimage.* 2019;184:901–915.

19. Ullmann E, Pelletier Paquette JF, Thong WE, Cohen-Adad J. Automatic labeling of vertebral levels using a robust template-based approach. *Int J Biomed Imaging.* 2014;2014:719520.
20. De Leener B, Fonov VS, Collins DL, Callot V, Stikov N, Cohen-Adad J. PAM50: unbiased multimodal template of the brainstem and spinal cord aligned with the ICBM152 space. *Neuroimage*. 2018;165:170–179.
21. De Leener Bea. Spinal cord toolbox. https://spinalcordtoolbox.com/user_section/tutorials.html
22. Zheng Y, Lee JC, Rudick R, Fisher E. Long-term magnetization transfer ratio evolution in multiple sclerosis white matter lesions. *J Neuroimaging.* 2018;28(2):191-198.
23. Cloney MB, Smith ZA, Weber KA 2nd, Parrish TB. Quantitative magnetization transfer MRI measurements of the anterior spinal cord region are associated with clinical outcomes in cervical spondylotic myelopathy. *Spine.* 2018;43(10):675-680.
24. Paliwal M, Weber KA 2nd, Hopkins BS, et al. Magnetization transfer ratio and morphometrics of the spinal cord associates with surgical recovery in patients with degenerative cervical myelopathy. *World Neurosurg.* 2020;144:e939-e947.
25. Perone CS, Calabrese E, Cohen-Adad J. Spinal cord gray matter segmentation using deep dilated convolutions. *Sci Rep.* 2018;8(1):5966.
26. Paquin M, El Mendili MM, Gros C, Dupont SM, Cohen-Adad J, Pradat PF. Spinal cord gray matter atrophy in amyotrophic lateral sclerosis. *AJNR Am J Neuroradiol.* 2018;39(1):184-192.
27. Bédard S, Valošek J, Seif M, et al. Normalizing spinal cord compression morphometric measures: application in degenerative cervical myelopathy. *MedRxiv.* 2024.
28. Hopkins BS, Weber KA 2nd, Cloney MB, Paliwal M, Parrish TB, Smith ZA. Tract-specific volume loss on 3T MRI in patients with cervical spondylotic myelopathy. *Spine.* 2018;43(20):e1204-e1209.
29. Grabher P, Mohammadi S, Trachsler A, et al. Voxel-based analysis of grey and white matter degeneration in cervical spondylotic myelopathy. *Sci Rep*. 2016;6:24636.
30. Martin AR, De Leener B, Cohen-Adad J, et al. A novel MRI biomarker of spinal cord white matter injury: T2*-weighted white matter to gray matter signal intensity ratio. *AJNR Am J Neuroradiol.* 2017;38(6):1266-1273.
31. Bédard S, Karthik EN, Tsagkas C, et al. Towards contrast-agnostic soft segmentation of the spinal cord. Preprint, Arxiv. 2024.
32. Naga Karthik E, Valošek J, Smith AC, et al. SCIseg: automatic segmentation of intramedullary lesions in spinal cord injury on T2-weighted MRI scans. *Radiol Artif Intell.* 2025;7(1):e240005.
33. Karthik EN, Valošek J, Farner L, et al. SCIsegV2: a universal tool for segmentation of intramedullary lesions in spinal cord injury. Arxiv, preprint. 2024.
34. Karthik EN, Valosek J, Smith AC, et al. SCIseg: automatic segmentation of T2-weighted intramedullary lesions in spinal cord injury. *Radiology: Artificial Intelligence*. 2024. doi:10.1148/ryai.240005.

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Supplemental Digital Content 1. Additional Content. MRI data acquisition and analysis hardware. **Figure 1.** Flowchart outlining the patient recruitment process from initial identification through screening and enrollment.