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

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Background: Cervical spondylotic myelopathy (CSM) is a progressive spinal condition that is often managed surgically. Knowledge of important predictors of surgical outcome can provide decision support to surgeons and enable them to effectively manage their patients' expectations. The purpose of this study was to identify the most important clinical predictors of surgical outcome in patients with CSM using data from two multinational prospective studies.

Methods: A total of 757 patients treated surgically for CSM participated in either the CSM-North America or the CSM-International study. The model was designed to distinguish between patients who achieved a modified Japanese Orthopaedic Association (mJOA) score of ≥16 at the one-year follow-up and those who did not (mJOA < 16). A score of 16 was chosen as the cutoff as an mJOA of ≥16 translates to minimal impairment. Univariate analyses evaluated the relationship between outcome and various clinical predictors. Multivariate Poisson regression was used to create the final prediction rule and estimate relative risks.

Results: Based on univariate analyses, the probability of achieving a score of ≥16 decreased with the presence of certain symptoms, including gait dysfunction, the presence of certain signs such as lower limb spasticity, positive smoking status, higher comorbidity score, more severe preoperative myelopathy, and older age. The final model consisted of six significant and clinically relevant predictors: baseline severity score (relative risk [RR], 1.11; 95% confidence interval [CI], 1.07 to 1.15), impaired gait (RR, 0.76 [ref. = absence]; 95% CI, 0.66 to 0.88), age (RR, 0.91 per decade; 95% CI, 0.85 to 0.96), comorbidity score (RR, 0.93; 95% CI, 0.88 to 0.98), smoking status (RR, 0.78 [ref. = non-smoking]; 95% CI, 0.65 to 0.93), and duration of symptoms (RR, 0.95; 95% CI, 0.90 to 0.99).

Conclusions: Patients were more likely to achieve a score of ≥16 (indicating minimal impairment) if they were younger, had milder preoperative myelopathy, did not smoke, had fewer and less severe comorbidities, did not present with impaired gait, and had shorter symptom duration.

Level of Evidence: Prognostic Level II. See Instructions for Authors for a complete description of levels of evidence.

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Cervical spondylotic myelopathy (CSM) is a degenerative spinal condition and the most common cause of spinal cord dysfunction worldwide[1-3]. Based on recent prospective multicenter studies, surgery may be beneficial for patients with CSM as it arrests deterioration and also improves neurological outcomes, functional status, and quality of life in

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TABLE I Patient Baseline Demographic Information and One-Year Functional Outcomes Following Surgery for CSM*

Variable	Total Sample	Severe Patients, mJOA < 12
Baseline mJOA severity score	12.52 ± 2.74 (3-17)	9.42 ± 1.67 (3-11)
Age *(yr)*	56.48 ± 11.85 (21-87)	60.09 ± 12.06 (28-86)
Male	463 (62.31%)	153 (60.24%)
Duration of symptoms *(mo)*	26.79 ± 39.25 (0.25-432)	24.43 ± 33.30 (0.25-240)
Smoker	199 (26.78%)	71 (27.95%)
Comorbidity score	1.45 ± 1.82 (0-13)	1.77 ± 1.99 (0-13)
Comorbidities	459 (61.78%)	172 (67.72%)
Cardiovascular	334 (44.95%)	141 (55.51%)
Respiratory	80 (10.77%)	29 (11.42%)
Gastrointestinal	120 (16.15%)	35 (13.78%)
Renal	22 (2.96%)	11 (4.33%)
Endocrine	135 (18.17%)	55 (21.65%)
Psychiatric	103 (13.86%)	30 (11.81%)
Rheumatologic	38 (5.11%)	18 (7.09%)
Neurological	47 (6.33%)	21 (8.27%)
Diagnosis		
Spondylosis	574 (77.25%)	204 (80.31%)
Disc herniation	533 (71.74%)	178 (70.08%)
OPLL	157 (21.13%)	57 (22.44%)
HLF	180 (24.23%)	73 (28.74%)
Subluxation	43 (5.79%)	17 (6.69%)
Symptoms, n = 742		
Numb hands	664 (89.49%)	240 (94.86%)
Clumsy hands	556 (74.93%)	225 (88.93%)
Impaired gait	568 (76.55%)	244 (96.44%)
Bilateral arm paresthesia	422 (56.87%)	169 (66.80%)
L'Hermitte phenomena	198 (26.68%)	74 (39.25%)
General weakness	615 (82.88%)	235 (92.89%)
Signs, n = 742		
Corticospinal motor deficits	406 (62.80%)	196 (77.47%)
Atrophy of intrinsic hand muscles	268 (36.12%)	120 (47.43%)
Hyperreflexia	578 (77.90%)	207 (81.82%)
Positive Hoffman sign	465 (62.67%)	168 (66.40%)
Upgoing plantar responses	266 (35.85%)	124 (49.01%)
Lower limb spasticity	353 (47.57%)	161 (63.64%)
Broad-based unstable gait	442 (59.57%)	209 (82.61%)
mJOA score at 1 year, n = 614 and 201	15.18 ± 2.66 (5-18)	13.73 ± 2.90 (5-18)
≥16	324 (52.77%)	64 (31.84%)
<16	290 (47.23%)	137 (68.16%)
≥12	553 (90.07%)	154 (76.62%)
<12	61 (9.93%)	47 (23.38%)

*Variables are given as the mean and standard deviation with the range in parentheses or as the number with the percentage in parentheses.
OPLL = ossification of the posterior longitudinal ligament, and HLF = hypertrophy of the ligamentum flavum.

patients with mild, moderate, and severe disease[4]. However, it still remains a challenge to accurately predict who is likely to benefit the most from surgical intervention.

Predicting surgical outcome in these patients is an increasingly important research topic. This information, in the form of a clinical prediction rule, would be valuable to clinicians

TABLE II Univariate Analyses Evaluating the Association Between Various Clinical Predictors and an mJOA Score of ≥16 at One Year Following Surgery*

Predictor	Relative Risk	95% CI	P Value
Baseline mJOA severity score	1.15	1.12 to 1.18	<0.0001
Age, per decade	0.84	0.80 to 0.88	<0.0001
Sex, ref. = female	0.91	0.78 to 1.06	0.21
Duration of symptoms†	0.96	0.91 to 1.01	0.14
Smoker, ref. = no	0.82	0.68 to 0.99	0.038
Comorbidity score‡	0.89	0.83 to 0.94	<0.0001
Comorbidities, ref. = absence	0.79	0.68 to 0.92	0.0017
Cardiovascular	0.71	0.60 to 0.84	<0.0001
Respiratory	0.80	0.60 to 1.07	0.13
Gastrointestinal	1.15	0.95 to 1.38	0.14
Renal	1.01	0.62 to 1.63	0.96
Endocrine	0.82	0.66 to 1.03	0.091
Psychiatric	0.93	0.74 to 1.16	0.51
Rheumatologic	0.91	0.64 to 1.31	0.63
Neurological	0.84	0.59 to 1.20	0.34
Symptoms, ref. = absence			
Numb hands	0.91	0.73 to 1.13	0.39
Clumsy hands	0.77	0.66 to 0.89	0.0007
Impaired gait	0.57	0.50 to 0.65	<0.0001
Bilateral arm paresthesia	0.82	0.71 to 0.95	0.0094
L'Hermitte phenomena	0.87	0.72 to 1.04	0.14
General weakness	0.70	0.60 to 0.81	<0.0001
Signs, ref. = absence			
Corticospinal motor deficits	0.71	0.61 to 0.82	<0.0001
Atrophy of intrinsic hand muscles	0.90	0.76 to 1.05	0.18
Hyperreflexia	0.83	0.70 to 0.97	0.020
Positive Hoffman sign	0.92	0.79 to 1.07	0.30
Upgoing plantar responses	0.75	0.63 to 0.89	0.0011
Lower limb spasticity	0.72	0.61 to 0.84	<0.0001
Broad-based unstable gait	0.57	0.49 to 0.66	<0.0001

*Relative risk for each variable was calculated using log-binomial regression. †Relative risk is per duration category; the 5 categories were ≤3 mo, >3 mo but ≤6 mo, >6 mo but ≤12 mo, >12 mo but ≤ 24 mo, and >24 mo. ‡The comorbidity score reflects both the number and severity of comorbidities. A 1-point increase reflects an increase in disease severity or in the number of comorbidities.

because it (1) helps to appropriately manage patients' expectations and, as a result, improves overall satisfaction[5]; (2) provides decision-making support to surgeons and identifies ways to optimize results; (3) gives surgeons a quantitative tool to accurately and objectively discuss prognostic information during the consent conversation; and (4) aligns surgeons' perceptions of outcomes across hospitals, regions, and even countries.

In part one of a three-part study, we designed a clinical prediction model to predict postoperative functional outcomes using prospective data on 278 patients enrolled in the multicenter AOSpine CSM-North America study[6]. This model was developed to distinguish between patients with an mJOA (modified Japanese Orthopaedic Association) score of ≥16 at one year postoperatively and those with substantial residual neurological dysfunction (mJOA < 16). This cutoff of 16 was later validated; on average, patients who demonstrated a minimal clinically important difference (MCID) on the mJOA had a one-year postoperative mJOA score (and standard deviation) of 16.02 ± 2.10. Based on this model, patients were more likely to achieve a score of ≥16 if they were younger, had a shorter duration of symptoms and milder myelopathy, did not smoke, and did not have depression or bipolar disorder or impaired gait. In part two, the external validity of this prediction rule was examined using data from 479 patients who participated in the AOSpine CSM-International study at sixteen global sites[7]. This model proved to be externally valid;

TABLE III Final Clinical Model to Predict Functional Status (mJOA ≥ 16) at One Year Following Surgery*

Predictor	Relative Risk	95% CI	P Value
Baseline mJOA severity score	1.11	1.07 to 1.15	<0.0001
Impaired gait, ref. = absence	0.76	0.66 to 0.88	0.0002
Age, per decade	0.91	0.85 to 0.96	0.0015
Comorbidity score†	0.93	0.88 to 0.98	0.0067
Smoker, ref. = no	0.78	0.65 to 0.93	0.0056
Duration of symptoms‡	0.95	0.90 to 0.99	0.029

*This model serves to distinguish between patients with mild myelopathy (mJOA ≥ 16 of 18) postoperatively and those with substantial residual neurological impairment (mJOA < 16). Relative risk for each covariate was calculated using Poisson regression. †The comorbidity score reflects both the number and severity of comorbidities. A 1-point increase reflects an increase in disease severity or in the number of comorbidities. ‡Relative risk is per duration category; the 5 categories were ≤3 mo, >3 mo but ≤6 mo, >6 mo but ≤12 mo, >12 mo but ≤ 24 mo, and >24 mo.

however, it was also evident that certain predictors were more relevant in North America than they were globally. The most significant of these was the presence of psychiatric disorders, which was highly significant in the North American study but was irrelevant in the international study.

Other limitations were identified in the two AOSpine CSM studies. One of the major concerns was that the model was better suited to predict outcome in patients with moderate (mJOA = 12 to 14) and mild (mJOA = 15 to 18) myelopathy. In severe cases, patients may exhibit substantial improvements on the mJOA but are less likely to achieve a final score of ≥16 at one year postoperatively. These patients would be classified as having a "suboptimal" outcome even though their gains in functional status were clinically meaningful.

The objective of this current study was to address certain limitations in our prediction rule and to refine the original model to increase global validity. This was done using the combined CSM-North America and CSM-International data set consisting of 743 patients from twenty-six sites.

Materials and Methods

Study Design and Sample

The CSM-North America and CSM-International studies are both prospective, multicenter cohort studies that were primarily undertaken to compare preoperative and postoperative neurological status and quality of life in patients with CSM. A secondary objective was to evaluate the most significant clinical predictors of surgical outcome and develop a clinical prediction rule that could guide practice.

Selected research sites were either academic centers or high-volume private practices. A total of twenty-six sites contributed patient data, including twelve in North America, six in Asia, five in Europe, and three in Latin America (Fig. 1). Eligible patients were approached by a research team and asked to participate in these studies if they (1) were eighteen years or older, (2) presented with symptomatic CSM, (3) displayed evidence of spinal cord compression on imaging, and (4) had not had previous spine surgery. Our definition of CSM encompassed patients with myelopathy secondary to spondylosis, disc desiccation, subluxation, or ligamentous aberrations, including ossification of the posterior longitudinal ligament. Patients were excluded if they were asymptomatic or if they had active infection, neoplastic disease, rheumatoid arthritis, ankylosing spondylitis, or concomitant lumbar stenosis. Written consent was obtained for each patient.

Surgical Intervention

All patients enrolled in these studies underwent surgical decompression of the spinal cord. For each case, the attending surgeon dictated the details of the procedure, including the approach, number of operative levels, and whether or not spinal fusion was performed. Patients treated with a posterior approach received a laminoplasty or a laminectomy with or without fusion. Anterior surgeries included cervical discectomy and/or corpectomy with or without fusion. In certain complex cases, patients received a two-stage circumferential (anterior and posterior) procedure.

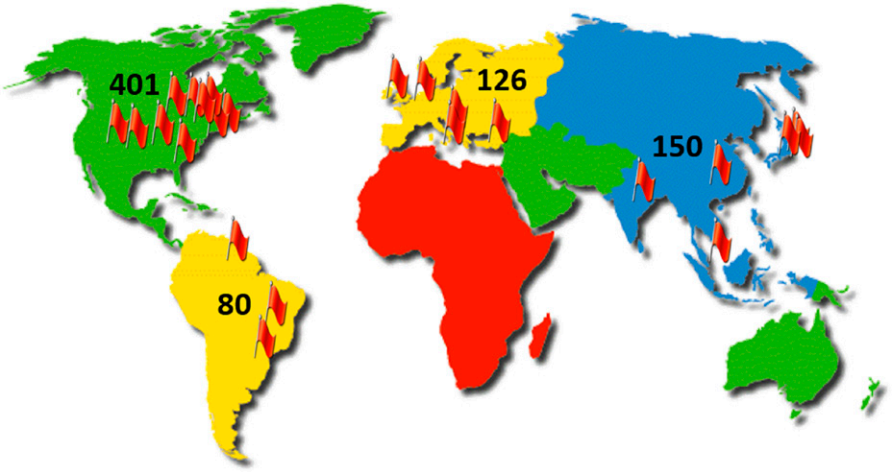

Fig. 1

Enrollment summary for the AOSpine CSM-North America and CSM-International studies. A total of 757 patients were enrolled at twenty-six global sites (twelve in North America, six in Asia, five in Europe, and three in Latin America), represented by the flags.

Data Collection

Using predesigned case report forms, extensive data were obtained for each patient at baseline and at twelve months following surgery, including demographics, symptomatology, imaging and clinical assessment, medical history, and previous conservative treatments. Functional status and health-related quality of life were evaluated at each visit using a variety of scales such as the mJOA, Neck Disability Index (NDI), Short Form (SF)-36, and thirty-meter walking test. This study was externally monitored.

Predictors

Figure 2 summarizes the predictors that were evaluated and whether or not they were significant in the North American study.

Outcome Measure

The mJOA was the primary outcome measure for this prediction study. This 18-point scale is an investigator-administered, CSM-specific index that evaluates functional status through assessment of upper and lower-extremity function, sensation, and micturition[8]. Recently, the psychometric properties of the mJOA were evaluated; this score demonstrated both convergent and divergent validity, internal consistency, and responsiveness[9]. The reliability of the mJOA has yet to be established, but the original scale (JOA) has both high interobserver and high intraobserver reliability[10].

The mJOA was dichotomized for the purpose of logistic regression analysis. A cutoff of 16 (mJOA ≥ 16, mJOA < 16) was deemed appropriate as it is within the range of mild myelopathy. Furthermore, this score can distinguish between patients with mild myelopathy and those with substantial residual neurological deficit. For patients with severe myelopathy (mJOA < 12), we developed a second prediction model and used a cutoff mJOA score of 12 (mJOA ≤ 12, mJOA > 12).

Statistical Analysis

Univariate log-binomial regression analyses were conducted to assess the relationship between various clinical factors and our primary outcome measure and to estimate relative risks. Predictors that yielded a p value of <0.2 in univariate analysis were further examined in multivariate analysis. Variables that were considered clinically relevant but had a p value of >0.2 were also assessed in multivariate analysis.

Multicollinearity was evaluated by calculating tolerance. Modified Poisson regression using robust error variances was used to create the final multivariate model and calculate the relative risk for each predictor. Variables were included in the final model if they were significant ($p < 0.05$) and/or deemed clinically important in the existing literature. Logistic regression analysis was performed on the final model to obtain a receiver operating characteristic (ROC) curve. An ROC curve plots the true positive rate against the false positive rate. The area under the curve (AUC) indicates the predictive performance of the model: an area of 1 reflects a test with 100% specificity and 100% sensitivity, whereas an area of 0.5 indicates no discriminative value.

Source of Funding

This study was externally sponsored by AOSpine International and AOSpine North America.

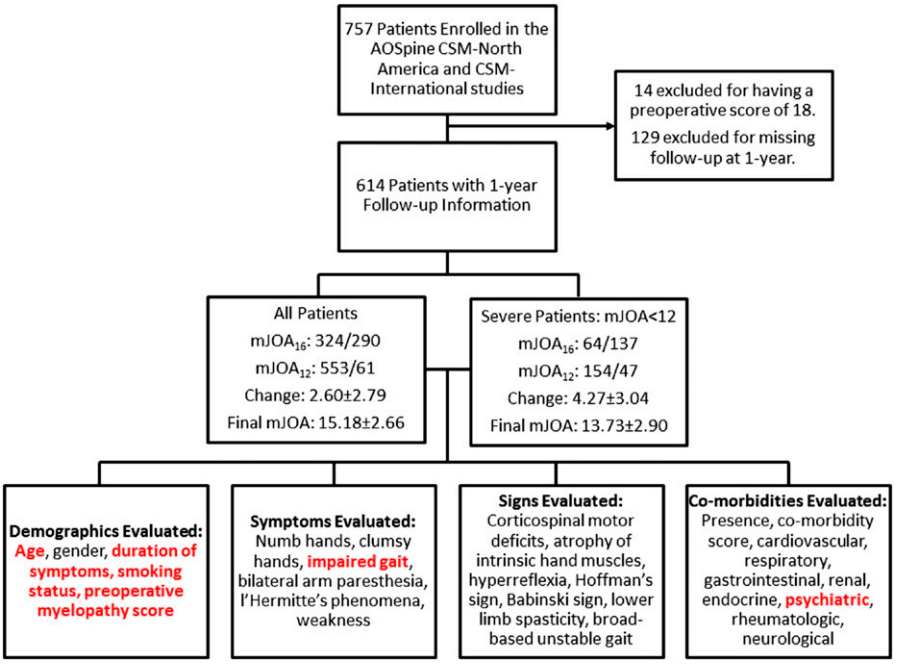

Fig. 2

Summary of participating subjects and predictors evaluated in this study. This figure summarizes the functional status at one year postoperatively of all 614 patients and of the 201 patients who had severe myelopathy (mJOA < 12) preoperatively. The pair of values following "$mJOA_{16}$" and "$mJOA_{12}$" represents the numbers of patients who did/did not achieve the indicated score of 16 or 12 on the mJOA at one year postoperatively. The value following "Change" represents the mean change in the mJOA from baseline to one year postoperatively. Predictors bolded in red were significant in our previous CSM-North America prediction study. The five symptom duration categories were less than or equal to three, more than three but less than or equal to six, more than six but less than or equal to twelve, more than twelve but less than or equal to twenty-four, and more than twenty-four months. The total comorbidity score is the sum across all comorbidity categories; for each comorbidity, mild disease = 1, moderate disease = 2, and severe disease = 3. Symptoms, signs, and comorbidities were considered either present or absent.

TABLE IV Univariate Analyses Evaluating the Association Between Various Clinical Predictors and an mJOA Score of ≥12 at One Year Following Surgery in Patients with Severe CSM (mJOA < 12)*

Predictor	Relative Risk	95% CI	P Value
Baseline mJOA severity score	1.07	1.02 to 1.13	0.010
Age, per decade	0.97	0.95 to 0.99	0.0014
Sex, ref. = female	0.98	0.84 to 1.14	0.81
Duration of symptoms†	0.96	0.92 to 1.01	0.087
Smoker, ref. = no	1.00	0.85 to 1.19	0.97
Comorbidity score‡	0.96	0.92 to 1.01	0.10
Comorbidities, ref. = absence	0.97	0.83 to 1.14	0.72
Cardiovascular	0.89	0.76 to 1.03	0.12
Respiratory	0.79	0.56 to 1.12	0.18
Gastrointestinal	0.95	0.74 to 1.21	0.67
Renal	1.15	0.87 to 1.51	0.32
Endocrine	1.05	0.88 to 1.25	0.59
Psychiatric	0.94	0.72 to 1.23	0.67
Rheumatologic	0.93	0.66 to 1.30	0.66
Neurological	0.98	0.73 to 1.31	0.88
Symptoms, ref. = absence			
Numb hands	0.83	0.68 to 1.02	0.080
Clumsy hands	0.93	0.75 to 1.15	0.50
Impaired gait	0.87	0.66 to 1.14	0.32
Bilateral arm paresthesia	0.90	0.77 to 1.04	0.15
L'Hermitte phenomena	0.84	0.70 to 1.02	0.087
General weakness	0.92	0.73 to 1.17	0.51
Signs, ref. = absence			
Corticospinal motor deficits	0.93	0.79 to 1.10	0.40
Atrophy of intrinsic hand muscles	1.03	0.89 to 1.20	0.68
Hyperreflexia	0.83	0.72 to 0.96	0.010
Positive Hoffman sign	0.88	0.76 to 1.03	0.10
Upgoing plantar responses	0.94	0.80 to 1.09	0.40
Lower limb spasticity	0.75	0.65 to 0.86	<0.0001
Broad-based unstable gait	0.89	0.75 to 1.06	0.19

*Relative risk for each variable was calculated using log-binomial regression. †Relative risk is per duration category; the 5 categories were ≤3 mo, >3 mo but ≤6 mo, >6 mo but ≤12 mo, >12 mo but ≤ 24 mo, and >24 mo. ‡The comorbidity score reflects both the number and severity of comorbidities. A 1-point increase reflects an increase in disease severity or in the number of comorbidities.

Results

Subjects

A total of 479 patients participated in the CSM-International study and 278 participated in the CSM-North America study at twenty-six global sites (Fig. 1). Of these 757 participants, fourteen were excluded from this analysis because they had a preoperative mJOA score of 18 out of 18. Six hundred and fourteen (82.6%) of the remaining 743 attended the one-year follow-up visit and were evaluated for improvements in functional status.

Our cohort consisted of 463 men (62.31%) and 280 women (37.69%), with a mean age at the time of surgery of 56.48 ± 11.85 years (range, twenty-one to eighty-seven years). Patients had a wide range of myelopathy severity, from 3 to 17 points on the mJOA scale, and a mean score of 12.52 ± 2.74. One hundred and ninety-three patients presented with myelopathy that was mild (mJOA = 15 to 17); 296, moderate (mJOA = 12 to 14); and 254, severe (mJOA < 12). With respect to degenerative diagnosis, 77.25% of patients displayed evidence of spondylosis; 71.74%, disc herniation; and 24.23%, a hypertrophied ligamentum flavum. A smaller percentage of patients presented with ossification of the posterior longitudinal ligament (21.13%) and subluxation (5.79%). The mean symptom duration was 26.79 ± 39.25 months (range, 0.25 to 432 months).

At the one-year follow-up, the mean mJOA score was 15.18 ± 2.66, reflecting significant improvements compared with baseline ($p < 0.05$). Surgery resulted in clinically meaningful

TABLE V Final Clinical Model to Predict Functional Status (mJOA ≥ 12) at One Year Following Surgery in Patients with Severe CSM (mJOA < 12)*

Predictor	Relative Risk	95% CI	P Value
Lower limb spasticity, ref. = absence	0.76	0.66 to 0.87	<0.0001
Baseline mJOA severity score	1.09	1.03 to 1.15	0.0028
Duration of symptoms†	0.94	0.89 to 0.99	0.012
Comorbidity score‡	0.96	0.91 to 1.00	0.066

*This model serves to distinguish between patients with mild to moderate myelopathy postoperatively (mJOA ≥ 12 of 18) and those with severe residual neurological impairment (mJOA < 12). Relative risk for each covariate was calculated using Poisson regression. †Relative risk is per duration category; the 5 categories were ≤3 mo, >3 mo but ≤6 mo, >6 mo but ≤12 mo, >12 mo but ≤ 24 mo, and >24 mo. ‡The comorbidity score reflects both the number and severity of comorbidities. A 1-point increase reflects an increase in disease severity or in the number of comorbidities.

gains in neurological function and quality of life in patients with mild, moderate, and severe myelopathy. Three hundred and twenty-four (52.77%) of the patients achieved a score of ≥16 and had mild myelopathy postoperatively, whereas 290 (47.23%) of the patients still had substantial residual neurological dysfunction (mJOA < 16). The majority (90.07%) of patients improved to a score of ≥12; however, 9.93% had severe myelopathy postoperatively. Table I displays the demographic information and one-year outcomes for the entire cohort and for patients with severe myelopathy (mJOA < 12) preoperatively.

Predicting an mJOA of ≥16

Univariate Analysis

Based on univariate analysis, the significant predictors of an mJOA of ≥16 were a higher baseline mJOA score (relative risk [RR], 1.15; 95% confidence interval [CI], 1.12 to 1.18), younger age (RR, 0.84 per decade; 95% CI, 0.80 to 0.88), nonsmoking status (RR, 0.82 [ref. = nonsmoking]; 95% CI, 0.68 to 0.99), absence of cardiovascular comorbidities (RR, 0.71 [ref. = absence]; 95% CI, 0.60 to 0.84), a lower comorbidity score (RR, 0.89; 95% CI, 0.83 to 0.94), absence of clumsy hands (RR, 0.77 [ref. = absence]; 95% CI, 0.66 to 0.89), impaired gait (RR, 0.57 [ref. = absence]; 95% CI, 0.50 to 0.65), bilateral arm paresthesia (RR, 0.82 [ref. = absence]; 95% CI, 0.71 to 0.95) and general weakness (RR, 0.70 [ref. = absence]; 95% CI, 0.60 to 0.81), and absence of corticospinal motor deficits (RR, 0.71 [ref. = absence]; 95% CI, 0.61 to 0.82), hyperreflexia (RR, 0.83 [ref. = absence]; 95% CI, 0.70 to 0.97), upgoing plantar responses (RR, 0.75 [ref. = absence]; 95% CI, 0.63 to 0.89), lower limb spasticity (RR, 0.72 [ref. = absence]; 95% CI, 0.61 to 0.84), and broad-based unstable gait (RR, 0.57 [ref. = absence]; 95% CI, 0.49 to 0.66). In addition, the associations between an mJOA of ≥16 and duration of symptoms; gastrointestinal, respiratory, and endocrine comorbidities; L'Hermitte phenomena; and atrophy of intrinsic hand muscles yielded p values of <0.20 and were evaluated in multivariate analysis (Table II).

Multivariate Analysis

The final model consisted of six significant and clinically relevant predictors: baseline mJOA severity score (RR, 1.11; 95% CI, 1.07 to 1.15), impaired gait (RR, 0.76 [ref. = absence]; 95% CI, 0.66 to 0.88), age (RR, 0.91 per decade; 95% CI, 0.85 to 0.96), comorbidity score (RR, 0.93; 95% CI, 0.88 to 0.98), smoking status (RR, 0.78 [ref. = nonsmoking); 95% CI, 0.65 to 0.93), and duration of symptoms (RR, 0.95; 95% CI, 0.90 to 0.99) (Table III).

Based on relative risks, the probability of achieving a score of ≥16 on the mJOA (1) decreased by 5% when a patient has an increased duration of symptoms (e.g., from three months or less to between three and less than six months), (2) increased by 11% for each one-point increase in baseline mJOA score, (3) decreased by 9% for each decade increase in age, (4) decreased by 7% for each one-point increase in comorbidity score (an increase in disease severity or in the number of comorbidities), (5) decreased by 24% when a patient presents with gait impairment (versus no impairment), and (6) decreased by 22% when a patient smokes. The AUC for this model was 0.77 (95% CI, 0.73 to 0.80), reflecting good discriminative ability.

Predicting an mJOA of ≥12

Baseline severity score (RR, 1.07; 95% CI, 1.02 to 1.13), hyperreflexia (RR, 0.83 [ref. = absence]; 95% CI, 0.72 to 0.96), lower limb spasticity (RR, 0.75 [ref. = absence]; 95% CI, 0.65 to 0.86), and age (RR, 0.97 per decade; 95% CI, 0.95 to 0.99) were significant predictors of an mJOA of ≥12 in univariate analysis (Table IV).

The final model consisted of three significant variables and one clinically relevant predictor. Three of these had also been significant in the model in our previous studies: baseline severity score (RR, 1.09; 95% CI, 1.03 to 1.15), duration of symptoms (RR, 0.94; 95% CI, 0.89 to 0.99), and comorbidity score (RR, 0.96; 95% CI, 0.91 to 1.00). In addition, the neurological sign "lower limb spasticity" significantly added to the predictive performance of this model (RR, 0.76 [ref. = absence], 95% CI, 0.66 to 0.87). Based on relative risks, patients were more likely to achieve a score of ≥12 on the mJOA if they had a higher baseline mJOA score, a lower comorbidity score (fewer and less severe concomitant diseases), a shorter symptom duration, and no lower limb spasticity. The AUC for this model was 0.75 (95% CI, 0.67 to 0.83) (Table V).

Discussion

This study aimed to develop a clinical prediction rule to determine functional outcomes in patients undergoing surgery

for CSM. This was done using prospectively collected data on 743 patients enrolled in either the CSM-International or the CSM-North America multicenter study. We incorporated results from our original North American prediction study and external validation study to create a clinically relevant and globally valid model that could be implemented into surgical practice[6,7]. Based on our findings, patients were more likely to achieve a score of ≥16 on the mJOA if they were younger, had milder myelopathy and a shorter duration of symptoms preoperatively, did not smoke, had fewer and less severe comorbidities, and did not present with impaired gait. This model was similar to the one constructed in the North American population except that the predictor "psychiatric disorders" was replaced with a comorbidity score that summarizes overall preoperative health status. Depression and bipolar disease had a greater predictive value in North America because the reported prevalence was significantly larger among these patients than in our international sample. These differences may indicate regional differences in actual prevalence but likely reflect either surgical selection bias or cultural reluctance to admit to mental illness. Regardless, the low prevalence in populations outside of North America decreases the global validity of this predictor. Instead, we developed a comorbidity score to summarize a patient's overall preoperative general health status. This score takes into account both the number of comorbidities as well as the severity of the coexisting disease. This predictor was significant in our model and contributed to its overall predictive performance.

Along with comorbidity score, the prediction model consisted of age, symptom duration, preoperative myelopathy severity, smoking status, and impaired gait. Elderly patients may have a reduced ability to translate neurological recovery into functional improvements. There are several potential explanations for this association between age and outcome: (1) The elderly experience modifications to the spinal cord, including decreases in the numbers of γ-motor neurons, anterior horn cells, and myelinated fibers in the corticospinal tracts and posterior funiculus. (2) As CSM is a progressive disease, older patients are likely to have more substantial degenerative pathology and may require a more complex surgery. (3) Older patients tend to have reduced physiological reserves and more unassociated comorbidities that may affect outcome[11-15]. Nevertheless, we do not recommend that surgeons differentiate on the basis of chronological age; rather, they should consider a patient's physiological age and coexisting comorbidities. In general, however, age is associated with reduced postoperative recovery and so the expectations of elderly patients should be managed accordingly.

A longer duration of symptoms was significantly associated with a poor surgical outcome. Chronic compression of the spinal cord for a prolonged duration can result in irreversible histological changes including cystic necrosis, cavitation, and syrinx formation[16]. Surgical decompression may not be able to reverse all of these changes and, as a result, patients will not achieve optimal recovery. It is therefore essential that primary care physicians are able to recognize key signs and symptoms of CSM, differentiate between this disease and other mimicking diagnoses, identify patients at high risk of disease progression, and refer patients early for surgical consultation. This is especially critical given recent reports regarding the natural history of the disease. According to a systematic review from 2013, between 20% and 60% of patients with symptomatic CSM will deteriorate over time without surgical intervention[17]. As patients progress, they will exhibit an increase in functional impairment, a decrease in social independence, and more deleterious signs and symptoms such as impaired gait and lower limb spasticity[18]. According to our model, both a more severe mJOA score and gait dysfunction are significant predictors of a worse surgical outcome. This finding confirms the need to detect these patients at earlier disease stages. Furthermore, surgeons may choose to operate on patients with milder myelopathy rather than waiting for these patients to progress to a severity at which they will no longer achieve optimal results.

This model is not intended to identify patients who will benefit more from surgery than from nonoperative management. Rather, it serves to predict outcomes in patients with progressive, symptomatic myelopathy and failed previous conservative, nonoperative management. A randomized controlled trial is required to evaluate the relative efficacy of conservative versus surgical treatment; however, it would be unethical to deny surgery to patients with symptomatic progressive myelopathy.

Smokers were less likely to achieve a score of ≥16 on the mJOA at the one-year follow-up. Although previous studies have suggested that smoking results in higher rates of nonunion and wound infection[19], there were no significant differences between smokers and nonsmokers with respect to these complications in our cohort. Instead, we speculate that smoking is a surrogate for an unhealthy lifestyle, the presence of comorbidities, lower socioeconomic status, and poorer dietary choices. All of these variables could impact a patient's clinical outcomes and recovery, compliance with postoperative management programs, and access to post-surgical care. Further research is required to confirm these hypotheses; however, until this is done, smoking cessation should be encouraged prior to surgery.

This prediction model can effectively discriminate between patients who will achieve an "optimal" outcome at one year postoperatively and those who will not. Predicting an mJOA score of ≥16 is clinically relevant and especially useful to manage expectations. Although patients often ask about their chances of improvement, they also want to know whether surgery will result in greater social independence, an ability to perform day-to-day activities, and the resolution of their more deleterious signs and symptoms. A score of ≥16 translates to minimal impairment and functional independence, and thus predicting this score is meaningful to patients. This information should be used by surgeons during the surgical consent discussion to manage expectations and to counsel concerned patients and their families regarding potential treatment options. Based on two recent studies, preoperative expectations, and whether or not they are met through treatment, are a significant predictor of overall satisfaction[20]. It is therefore important that clinicians use our quantitative prediction tool to more objectively convey prognostic information and give the patient a better understanding of how he or she should expect to fare following intervention.

This current study also addresses another limitation of our original CSM-North America study. Patients with severe

myelopathy (mJOA < 12) have a significantly lower probability of achieving a score of ≥16 on the mJOA. It is unjust to classify a patient who improves from a score of 8 to a score of 14 as having a "suboptimal" outcome. We developed a second prediction model for these patients to evaluate their probability of improving to a score of ≥12 on the mJOA. Based on our findings, the most significant predictors of this outcome were baseline severity score, duration of symptoms, comorbidity score, and lower limb spasticity. Interestingly, even in patients with severe disease, the earlier surgeons intervene, the better patients are likely to do. Overall health status is also critical to a patient's surgical success; specifically, patients with severe myelopathy who are in good cardiovascular health are expected to fare better than those with concomitant cardiovascular disease.

In summary, patients were more likely to achieve a score of ≥16 on the mJOA if they were younger, had milder myelopathy and a shorter duration of symptoms preoperatively, did not smoke, had fewer and less severe comorbidities, and did not present with gait dysfunction. ■

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