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Myotome Conversion from Zero Reveals Recovery Beyond Pooled Motor Scores After Cervical Spinal Cord Injury: A Proof-of-Concept Analysis

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Abstract

Study Design: Retrospective proof-of-concept analysis
Objective: We propose myotome conversion from zero (MC-0) as a proof-of-concept analytic metric that can better differentiate segmental recovery patterns obscured by pooled motor scores and AIS grade.
Setting: Data from the Spinal Cord Injury Model Systems Database (SCIMS; 2016–2023).
Methods: Retrospective proof-of-concept analysis of participants with traumatic cervical SCI from the SCIMS Database. For each key upper-extremity myotome we tabulated the number of***low*** MC-0 (improvement to 1-2/5 from a baseline motor score of 0/5), and ***high*** MC-0 (improvement to ≥3/5 from a baseline of 0/5). We analyzed the proportion of upper-extremity myotomes demonstrating MC-0, the proportion without conversion, the distribution of conversion by neurological level of injury, and clinically meaningful UEMS changes, alongside AIS grade stability, between inpatient rehabilitation admission and discharge.
Results: 1,275 participants from 16 SCIMS sites were analyzed. Across 10 key myotomes (C5–T1, bilaterally), nearly half of initially paralyzed upper-extremity myotomes showed some recovery between rehabilitation admission and discharge (31.8% low, 14.3% high conversion), while 53.9% showed no conversion. MC-0 was operationalized using registry data and explained an additional 23–30% of variation in discharge UEMS beyond admission UEMS across C4–C6 injuries. Notably, many participants demonstrated myotome conversions across multiple key myotomes without a change in AIS grade.
Conclusion: MC-0 assessment is feasible in registry data and provides a more granular view of early motor recovery after cervical SCI. MC-0 may complement or replace traditional outcomes in natural history studies and early neurorecovery trials.

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Introduction

Estimating neurologic recovery after traumatic cervical SCI is essential for prognosis, rehabilitation planning, and interpretation of treatment effects[1-6]. Neurologic impairment after a spinal cord injury (SCI) is measured with the International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) examination (inclusive of motor, light touch, pin prick, and rectal assessments) and the American Spinal Injury Association Impairment Scale (AIS)[1,2,7]. However, commonly used summary outcomes derived from these assessments, including AIS grade and pooled motor scores, do not differentiate whether improvement reflects new activation of a previously silent myotome or strengthening within a muscle that already demonstrated voluntary activity[7]. These clinically distinct recovery patterns may contribute similarly to an aggregate motor score but may carry different implications for functional recovery and interpretation of treatment effects in the context of clinical trials of neurorecovery therapeutics. To address this limitation, we examined myotome conversion from zero (MC-0), defined as the recovery of voluntary motor output in a myotome that had a baseline motor score

of 0. MC-0 identifies the emergence of voluntary contraction in previously paralyzed segments, a recovery event that pooled motor scores and AIS grade can obscure.

The ISNCSCI contains the segmental information necessary to identify these recovery patterns, but conventional analyses collapse this information into pooled summary scores[7]. AIS grade, originally designed as a classification system, is inherently coarse as large degrees of neurological recovery can occur without crossing the categorical thresholds needed to register grade conversion. Similarly, ISNCSCI-derived total motor scores, including the Upper Extremity Motor Score (UEMS) and Lower Extremity Motor Score (LEMS), aggregate multiple recovery processes into a single composite value. As a result, these commonly reported summary measures describe overall impairment but do not distinguish recovery of a previously silent myotome from strengthening within an already active muscle group[3,7]. Because these recovery patterns may carry different implications for prognosis and for interpretation of treatment effects, distinguishing them is important when characterizing spontaneous recovery and when evaluating therapies in early-phase clinical trials[8].

To address this limitation, we previously proposed disaggregating total motor recovery into two complementary components: the first is *myotome conversion from zero (MC-0),* defined as the emergence of any voluntary strength in myotomes initially graded a 0/5. The second is *motor augmentation*, defined as an incremental gain in strength within myotomes that already exhibit at least trace voluntary activity ($\geq$1/5)[7]. While both contribute to changes in pooled motor scores, they represent distinct and clinically interpretable recovery trajectories and should not be treated as interchangeable[7].

In this proof-of-concept study, we evaluated whether MC-0 can be operationalized as a distinct analytic construct in a large multicenter registry dataset. Using data from the Spinal Cord Injury Model Systems Database (SCIMS), we examined whether MC-0 provides additional explanatory information about early upper extremity motor recovery during inpatient rehabilitation after traumatic cervical SCI beyond what is captured by pooled upper extremity motor scores (UEMS) and AIS grade. Demonstrating feasibility in a real-world dataset represents an important first step towards incorporating myotome-level recovery metrics into early-phase neurorecovery trials.

METHODS

Study design: This study was a retrospective observational analysis using data from the SCIMS database, a multicenter registry that prospectively collects longitudinal clinical data from individuals with traumatic SCI across the United States. All data used were deidentified prior to analysis. Institutional Review Board (IRB) approval was obtained at each participating center contributing to the SCIMS database, ensuring compliance with ethical standards for human subjects' research. Secondary analysis of the deidentified data was determined to be exempt from additional IRB review at our institution.

Inclusion and exclusion criteria: We selected all records in the SCIMS cohort from 2016-2023 with the following inclusion criteria: (1) presence of an event resulting in a traumatic cervical SCI, including

surgical procedures, radiation, or medical complications; (2) temporary or permanent sensory and/or motor impairment following a traumatic event; (3) hospitalization to inpatient acute rehabilitation; (4) age ≥18 years; (5) International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) assessments completed at four key time points, within the first 72 hours post-injury, at admission to rehabilitation, at discharge, and at one year post-injury; and (6) neurological level of injury at T1 or above. Exclusion criteria: (1) penetrating injuries such as stab or gunshot wounds.

Data Collection: Demographic characteristics and raw ISNCSCI examination data, including motor, sensory and AIS grade were obtained from the SCIMS database.

Outcome measures: The primary outcome was the proportion of upper extremity myotomes demonstrating conversion from zero (MC-0) between inpatient rehabilitation admission and discharge. MC-0 was defined as recovery of voluntary activity in a key muscle with a baseline motor grade of 0 at admission to ≥1 at discharge. Only myotomes with a baseline motor score of 0 at rehabilitation admission were considered eligible for MC-0 analysis, and proportions of low, high, and no conversion were calculated relative to this denominator.

Each conversion was evaluated across the ten key upper extremity myotomes (C5 through T1, bilaterally). To characterize different magnitudes of recovery, MC-0 events were stratified into two categories: (1) low conversion: motor grade improvement from 0/5 to 1/5 or 2/5; and (2) high conversion: motor grade improvement from 0/5 to ≥3/5.

Secondary outcomes included: the proportion of myotomes with no conversion; the distribution of conversion events by neurological level of injury (NLI); and the proportion of individuals achieving a small change (>2.98 points), and a substantial change (>7.45 points) in UEMS, based on effect size-based estimates reported by Scivoletto et al.[9] Participants were categorized according to admission-to-discharge UEMS change using previously reported distribution-based thresholds for clinically meaningful change (low <2.98, moderate 2.98–7.49, substantial >7.49), and the distribution of these categories was summarized alongside patient-level MC-0 categories within each NLI stratum. AIS grade conversions were also summarized among participants whose AIS grade remained unchanged between admission and discharge.

Data quality, missing data: SCIMS data undergo standardized quality assurance procedures, including automated range checks, logical validation algorithms, and periodic audits conducted by the National Spinal Cord Injury Statistical Center. Prior to analysis, the dataset was deidentified. Missing data were retained and reported at each stage of analysis.

Statistical Analysis: To assess whether patient-level MC-0 category was associated with variation in discharge motor outcome beyond admission UEMS alone, neurological level of injury (NLI)-stratified nested linear regression models were fit with discharge UEMS as the dependent variable. Because both MC-0 and discharge UEMS are derived from the neurological examination, the regression analysis was

interpreted as explanatory rather than prognostic. This analysis included participants who met both criteria:

1. Eligibility for MC-0 analysis (≥1 below NLI myotome with admission motor scores = 0), and
2. Non-missing UEMS totals at rehabilitation admission and discharge.

For each NLI level, two nested models were fit. Model 1 (baseline model) included admission UEMS as the sole predictor of discharge UEMS. Model 2 included admission UEMS and MC-0 category. MC-0 category was defined at the patient level according to the highest magnitude of conversion observed across below NLI myotomes:

- None: no conversion from zero;
- Low-only conversion from 0 to 1 or 2;
- High ≥1 conversion from 0 to ≥3 or more.

Model improvement was assessed using analysis of variance (ANOVA) comparing nested models. The change in explained variance was calculated as the difference in R^2 between Model 2 and Model 1. Effect size was quantified using partial eta squared, calculated from sums of square derived from the nested comparison. Regression assumptions were evaluated via inspection of residual plots for linearity and homoscedasticity, quantile-quantile plots for residual normality, variance inflation factors to assess multicollinearity, and Cook's distance to evaluate influential observations. No substantial violations were identified. Statistical significance was defined as <0.05. Analyses were performed using R (2026.01.0+392).

RESULTS

Cohort characteristics

Among individuals enrolled in SCIMS from 16 sites nationally (**N=1,275**), between 2016 and 2023; 77% were male; 70.6% were White, 22.5% Black/African American; 10.7% identified as Hispanic or Latino. Average age of the cohort at time of injury was 48.6±17.1 years. In terms of AIS severity, 17.8% of the cohort was categorized as AIS A, and 51.6% as AIS D at inpatient rehabilitation admission. The average days between injury and time to inpatient rehabilitation admission was 23.5±22.9 days (range: 0-211 days in 1,275 individuals). Average days between injury and time to discharge was 72.9±41 days (range: 8-336 days). The largest majority of this cohort (38.8%) presented with neurological level of injury (NLI) at C4. Table 1 contains detailed reports of the sociodemographic and clinical characteristics of the cohort between inpatient admission rehabilitation and discharge.

[ISNSERT TABLE 1 HERE]

Myotome conversion from zero between rehabilitation admission and discharge.

Across ten key myotomes (C5-T1 bilaterally), nearly half of initially paralyzed upper-extremity myotomes recovered to some degree between rehabilitation admission and discharge. Overall, 31.8% of eligible myotomes demonstrated low conversion, 14.3% demonstrated high conversion, 53.9% demonstrated no conversion. Recovery was most prominent at the C5-C6 levels, where over 40% of the initially completely paralyzed myotomes demonstrated low or high conversion. In contrast, C8-T1 myotomes exhibited relatively lower conversion rates, approximately 22%, consistent with the predominance of rostral injury levels in the cohort. Conversion patterns were broadly symmetrical across sides. Table 2 summarizes myotome-level conversion frequencies.

[INSERT TABLE 2 HERE]

The proportions of myotomes with no conversion (0à0) increased progressively from rostral to caudal segments. At the proximal segments (C5-6), approximately 45-57% of right-sided and 46-48% of the left-sided myotomes remained at 0 between admission and discharge. This proportion rose to 52-54% at C7 and exceeded 63% at the most distal segments (C8-T1). Right-left differences were small across all levels.

Distribution of conversion events by neurological level of injury

Table 3 summarizes the conversion events by neurological level of injury (NLI). Across NLIs C4–C6, the majority of eligible myotomes demonstrated no conversion (62.9%), whereas low conversion occurred in 23.3% and high conversion in 14.1% of myotomes bilaterally. At NLI C7, only two myotomes are available below the level of injury for potential conversion, resulting in a smaller sample size (n=21 right; n=23 left); within that limited sample, low conversion occurred in more than 40% of myotomes and high conversion in approximately 20%. These findings should be interpreted cautiously because of the small denominator at C7.

[INSERT TABLE 3 HERE]

Comparison of MC-0 categories with pooled UEMS change.

Table 4 summarizes, within each NLI stratum, the distribution of patient-level MC-0 categories and pooled UEMS change categories defined using previously reported distribution-based thresholds for clinically meaningful change. For this analysis, we included participants who had at least one myotome below their NLI with a baseline motor score of 0 and non-missing admission and discharge UEMS. Across NLIs C4–C6, the proportion of participants classified as MC-0 none ranged from 31.9% to 32.6%, MC-0 low-only ranged from 33.1% to 37.7%, and MC-0 high ranged from 30.4% to 34.5%. Over the same strata, the proportion of participants with low UEMS change (<2.98 points) ranged from 29.5% to 39.1%, moderate UEMS change (2.98–7.49 points) ranged from 27.3% to 37.7%, and substantial UEMS change (>7.49 points) ranged from 23.2% to 41.0%. The sample size at C7 was small and was interpreted descriptively.

[INSERT TABLE 4 HERE]

Explanatory contribution of MC-0 beyond admission UEMS

NLI-stratified nested linear regression models were used to examine whether patient-level MC-0 category accounted for additional variation in discharge UEMS after admission UEMS was included in the model. Because both MC-0 and discharge UEMS are derived from the discharge examination, these analyses were interpreted as explanatory rather than prognostic.

For C4 injuries (N = 374), admission UEMS alone explained 53.4% of the variance in discharge UEMS (R^2 = 0.534). Addition of MC-0 category improved model fit ($F(2,370) = 334.44$, $p < 0.001$), increasing explained variance to 83.4% (R^2 = 0.834), representing a ΔR^2 of 0.300. The corresponding effect size was large (partial $\eta^2 \approx 0.64$). For C5 injuries (N = 139), admission UEMS explained 58.0% of discharge variance (R^2 = 0.580). Inclusion of MC-0 category improved model fit ($F(2,135) = 82.98$, $p < 0.001$), increasing explained variance to 81.2% (R^2 = 0.812), with ΔR^2 = 0.231. The associated partial η^2 was 0.55. For C6 injuries (N = 69), admission UEMS alone explained 46.9% of variance in discharge UEMS (R^2 = 0.469). Addition of MC-0 category improved model fit ($F(2,65) = 26.83$, $p < 0.001$), increasing explained variance to 70.9% (R^2 = 0.709), with ΔR^2 = 0.240. The corresponding partial η^2 was approximately 0.45.

Across cervical injury levels C4–C6, MC-0 consistently explained an additional 23–30% of variance in discharge motor strength after accounting for baseline UEMS.

AIS Grade Transitions and MC-0 despite unchanged AIS grade

AIS grade transitions between rehabilitation admission and discharge were broadly consistent with expected patterns of recovery after traumatic cervical SCI. Among individuals admitted as AIS A, 24% improved by at least one AIS grade; among those admitted as AIS B, overall conversion exceeded 40%; among those admitted as AIS C, 54% improved by at least one grade; and nearly all individuals admitted as AIS D remained stable. Detailed AIS transition frequencies are presented in Supplemental Table 1.

MC-0 events were observed among participants whose AIS grade remained unchanged between admission and discharge. In the AIS A à A subgroup, segmental recovery was still observed across multiple cervical myotomes, and similar patterns were presented in the AIS B à B and AIS C àC subgroups. These descriptive findings highlight myotome-level recovery even in the absence of AIS grade conversions. Supplemental Table 2 summarizes these subgroup analyses.

DISCUSSION

In this proof-of-concept analysis, we demonstrated that myotome conversion from zero (MC-0) can be operationalized in a large real-world spinal cord injury registry, and it produces recovery information that is not directly visible in pooled motor scores or AIS grade. Across cervical injury levels C4-C6, patient-level MC-0 category accounted for an additional 23-30% of variation in discharge UEMS after admission UEMS was included in the model. Because both MC-0 and discharge UEMS are derived from the discharge examination, this analysis is best interpreted as explanatory rather than prognostic.

Nonetheless, the findings support the central premise of this study: pooled motor scores summarize the magnitude of recovery, whereas MC-0 helps identify one specific pattern of recovery, namely the emergence of voluntary activity in previously silent myotomes.

This distinction is clinically relevant because equivalent pooled UEMS gains may arise from different segmental patterns of recovery. A given amount of total motor score change may reflect strengthening across muscles that already had baseline activity, recovery within a small number of previously paralyzed myotomes, or a combination of both. By identifying when voluntary output emerges in myotomes that were graded 0 at admission, MC-0 provides a more granular description of early upper extremity motor recovery than pooled scores alone.

Analyses of multiple SCI datasets have reported approximately a 10-point spontaneous improvement in UEMS, with an average gain of about six points within the first six months post-injury[3,10-12]. As estimated by Scivoletto et al.[9], if a 7.45 UEMS point improvement occurs on all the 10 key muscles of the upper extremities (less than 1 point per muscle), this is of little meaningfulness as improvement of multiple muscles from a baseline grade of 3/5 to 4/5 or 5/5 is not equivalent to recovery to antigravity motor strength from a baseline grade of 0/5. This better aligns the definition of clinical significance proposed by Kramer et al[3].

With the proposed use of MC-0 as a more granular outcome measure, we are providing an independent and substantial explanatory value beyond aggregate motor scores. Importantly, regardless of the proposed MCID or MID thresholds, the segmental distribution of UEMS gains may be more clinically informative than the absolute change in the total score. Our findings support the mechanistic disaggregation of motor recovery and demonstrate that MC-0 captures clinically meaningful recovery signals not reflected in baseline or summed motor scores alone. Whether such recovery manifests as a trace contraction or as the re-establishment of antigravity strength, its biological implications differ fundamentally from those of incremental strengthening within an already innervated segment. Evidence from clinical neurophysiology supports this interpretation[13-16]. In other words, MC-0 allows us to identify the magnitude and location of recovery on those previously paralyzed muscles regaining function, information that is obscured when recovery is assessed solely through pooled measures such as UEMS.

The descriptive comparison with pooled UEMS threshold categories further supports this interpretation. Within the same NLI strata, the distribution of MC-0 categories differed from the distribution of pooled UEMS change categories, indicating that myotome conversion from zero and pooled motor score change provide different descriptive summaries of recovery. Rather than replacing pooled motor scores, MC-0 complements them by identifying a segmental recovery pattern that aggregate scores cannot localize.

Regarding AIS grade change, our results were largely consistent with those reported in the literature[10,17-19]. Although comparing myotome conversion with AIS grade change is not entirely equivalent, since AIS classification incorporates not only motor improvement but also sensory function

and sacral sparing, it is noteworthy that meaningful MC-0 occurred without AIS grade change. This finding is consistent with the results of MC-0 detecting recovery signals that established measures may not capture. The SCI population is highly heterogeneous, even among individuals sharing the same AIS grade or neurologic level of injury, and this heterogeneity is inadequately addressed by summed motor scores.

Composite measures such as TMS, UEMS, and LEMS aggregate motor change into a single value, thereby conflating at least two mechanistically distinct processes MC-0, which likely reflects neuroplastic reorganization or reinnervation of descending pathways, and change within already active muscles (motor augmentation), which may arise from a broader mix of mechanisms, including strengthening of spared circuits and rehabilitation-related gains. Applying the same aggregate metric across injury severities ignores differences in baseline impairment and masks biologically meaningful recovery. Acknowledging the psychometric limitations of the historical utilization of summed scores, our approach aims to explicitly separate recovery mechanisms at the myotome level. While the timing of neurological assessments with the ISNCSCI was highly variable, and frequently missing at 72 hrs and at 1-year post-injury. MC-0 provides independent explanatory value even within the compressed inpatient rehabilitation window, strengthening confidence in its utility across longer observation periods. Our findings intend to demonstrate how mechanistic disaggregation reveals recovery otherwise hidden within standard outcome measures.

Importantly, our intent is not to substitute or redefine the ISNCSCI, but to enhance its interpretive power as an outcome framework. Originally developed as a classification system, ISNCSCI has been widely adopted for evaluative purposes despite known psychometric constraints when used to detect clinically meaningful change. AIS grade transitions capture major categorical shifts in impairment but show limited sensitivity to nuanced, segmental recovery, particularly during early phases of spontaneous neurorecovery. By disaggregating ISNCSCI-derived motor scores into MC-0 and change within already active muscles, we preserve the strengths of ISNCSCI, its universality, reproducibility, and clinical accessibility, while addressing the limitations of composite scoring. This approach allows motor change to be interpreted in a biologically informed manner and better aligned with functionally meaningful outcomes, such as elbow extension for pressure relief, finger flexion for grasp, or independent catheterization. Future work will extend this framework to longer-term datasets, will integrate functional outcome measures, and will pursue prospective validation by incorporating MC-0 into early-phase clinical trial protocols, where it can be evaluated alongside neurophysiologic biomarkers to further clarify the biological substrates of early motor recovery.

LIMITATIONS:

This study has several limitations. First, the timing of neurological assessments was variable, particularly in the early phase after injury and at later follow-up time points, limiting detailed characterization of the full longitudinal recovery trajectory. Second, because MC-0 and discharge UEMS are both derived from the discharge motor examination, the nested regression analyses should be

interpreted as explanatory rather than predictive. Third, this initial analysis was limited to upper extremity motor recovery during inpatient rehabilitation. Additional work is needed to evaluate lower extremity myotomes and longer-term recovery trajectories. Finally, registry-based analyses are constrained by the timing and completeness of available clinical examinations. Replication of this analysis in a cohort with true baseline ISNCSCI examinations (performed within 72 hours to 7 days post-injury) at a standardized early time point will be important to more accurately characterize these early recovery events.

CONCLUSIONS

This proof-of-concept study demonstrates that MC-0 can be operationalized in registry data and provides a more granular description of early upper-extremity recovery after traumatic cervical SCI than pooled motor scores or AIS grade alone. Equivalent pooled motor score gains can arise from clinically different segmental recovery patterns, and MC-0 helps distinguish recovery of previously silent myotomes from change within muscles that already had baseline activity. These findings support further evaluation of MC-0 as a key analytic metric in natural-history studies and early-phase neurorecovery trials.

Declarations

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Conflicts of Interest: The authors declare no conflicts of interest.

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Tables

Tables 1 to 4 are available in the supplementary files section

Supplementary Files

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