



Original Article

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Impact of Mechanism of Injury on Long-term Neurological Outcomes of Cervical Sensorimotor Complete Acute Traumatic Spinal Cord Injury

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Objective: Mechanism of injury is a largely understudied descriptor of acute traumatic spinal cord injury (tSCI). This study sought to compare the impact of high-energy and low-energy mechanisms of injury in neurological outcomes of cervical sensorimotor complete tSCI.

Methods: Patients with tSCI were identified in 4 prospective, multicenter clinical trials and registries. American Spinal Injury Association Impairment Scale (AIS) grade was assessed ≤ 72 hours postinjury and followed up between 12 to 52 weeks. Patients were included if they had a cervical and sensorimotor complete (AIS-A) injury at baseline. Study outcomes were change in AIS grade and lower extremity motor, upper extremity motor, and total motor scores. Propensity score matching between high-energy mechanisms of injury (HEMI; e.g., motor vehicle collisions) and low-energy mechanisms of injury (LEMI; e.g., falls) groups was performed. Adjusted groups were compared with paired t-tests and McNemar test.

Results: Of 667 patients eligible for inclusion, 523 experienced HEMI (78.4%). HEMI patients were younger, had lower body mass index, more associated fractures or dislocations, and lower baseline lower extremity motor scores. After propensity score matching of these baseline variables, 118 pairs were matched. HEMI patients had a significantly worse motor recovery from baseline to follow-up based on their diminished change in upper extremity motor scores and total motor scores.

Conclusion: Cervical sensorimotor complete tSCIs from HEMI were associated with significantly lower motor recovery compared to LEMI patients. Our findings suggest that mechanism of injury should be considered in modelling prognosis and in understanding the heterogeneity of outcomes after acute tSCI.

Keywords: Spinal cord injury, Injury mechanism, Cervical spinal cord injury, Neurological outcomes, Motor recovery



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INTRODUCTION

Over the last few decades there seems to be a shift in the demographic composition of spinal cord injury (SCI). The prevalence of the disease, however, has remained stable imposing significant burden on health care systems across the globe. The Global Burden of Disease Study published in the Lancet provided insights into the global prevalence and incidence of SCI

between 1990–2016, and overall found that the prevalence of SCI has been stable over the aforementioned 26-year period.^{1,2} The incidence rate was found to be 13 per 100,000 people and a prevalence of 27.04 million.² North American Data on SCI suggests 39 per million cases of traumatic SCI (tSCI), with Canadian published data reporting an incidence in 2010 of 41 per million for tSCI.³⁻⁶

The majority of tSCIs are in the cervical spine (60%), with over-

all mortality largely due to cervical level injuries resulting in respiratory failure.^{7,8} Overtime there has been a bimodal distribution in the age of patients due to the ongoing presence of motor vehicle collisions (MVCs) in young adults, particularly males, and the aging population having superimposed falls with pre-existing degenerative pathologies, more commonly in women.^{3,6,9-13} This has been demonstrated in various studies showing a change in the average age of patients from the early 30s to, more recently, patients in their mid to late 40s.^{5,14} From the 1970s to the early 2000s those over 60 represented only 4.7% of the SCI database, while this representation rose to 10% and is continuing to rise, commensurate with the aging population.^{3,7} Selvarajah et al.¹⁵ recently reported falls to be the cause of 41.5% of tSCI with MVCs following behind at 35.5%. While demographics and etiology have been thoroughly studied, there is a paucity of literature assessing the impact of the energy of the mechanism of injury on cervical outcomes; typically with MVCs and sports injuries characterized as high-energy (high-energy mechanisms of injury, HEMI) and falls being low-energy (low-energy mechanisms of injury, LEMI).^{3,12}

Intuitively, one would suspect that HEMIs result in more severe injury patterns. The difference in pathology is hypothesized to be due to the extent of tissue injury and that the primary injury in HEMI results in intrinsic cord disruption while LEMI pathology is due to ongoing secondary compression.¹⁶⁻¹⁹ In animal models, Noyes²⁰ found that peak force and displacement were predictors of injury while Dohrmann and Panjabi²¹ report on momentum and impulse determining injury – both studies allow us to extrapolate that HEMI would result in more severe injury. Animal models in ferrets by Kearney et al.²² explore the impact of velocity and compression on the extent of injury, wherein the increasing product of velocity and compression results in increasing injury severity at higher velocities. This similarly allows us to infer that HEMIs, which are of higher velocity and compression, will result in more severe injury.²² Lenahan et al.¹² have found that incomplete injuries, less severe than complete injuries, are more common in the elderly; this could be owing to the fact that the energy of impact most commonly affecting this population is lower. The aim of our study is to explore whether the initial mechanism of energy affects patient outcomes in those with complete cervical injuries, thus identifying factors that alter outcomes which will assist with acute and long-term patient management. We isolated the complete tSCI population as there is significant uncertainty in the natural history of their disease. We postulate that the mechanism of injury plays a role in the neurological recovery of complete cervical

tSCI patients.

MATERIALS AND METHODS

1. Data Sources, Participants, and Eligibility Criteria

We pooled individual patient data from 4 high-quality, prospective, multicenter acute SCI databases from December 1991 to March 2017, as previously described.²³ This study design and data permitted a powerful quantitative analysis on highly granular patient, injury, and interventional factors for traumatic SCI outcome measures at long-term follow-up. The 4 databases that were combined included the North American Clinical Trials Network (NACTN) SCI Registry,²⁴ the Sygen Trial,²⁵ the Surgical Timing in Acute Spinal Cord Injury Study (STASCIS),²⁶ and the National Acute Spinal Cord Injury Study III.²⁷

Patients with acute traumatic SCI were identified in the combined dataset. Patients were eligible if they had a cervical neurological level of injury that was evaluated as sensorimotor complete through the American Spinal Injury Association Impairment Scale (AIS) with a grade of A within 72 hours of initial injury. Included patients were followed up between 12 to 52 weeks after initial admission. Comparison groups were HEMI defined as injuries from motor vehicle collisions and sports injuries, and LEMI defined as injuries from falls.

2. Outcomes

The study endpoint was neurological recovery evaluated with a change in AIS grade by at least one grade (i.e., from A to B or greater) and motor recovery evaluated with a change in lower extremity motor score (LEMS), upper extremity motor score (UEMS) and total motor scores (TMS) from baseline to follow-up between 12 to 52 weeks. The 52-week follow-up timepoint was selected as the end range as previous literature has shown that most of the recovery after acute SCI has occurred by this time, with minimal recovery observed afterwards.²⁸

3. Statistical Analysis

Descriptive statistics were calculated with means and standard deviations (SDs) for continuous variables and absolute numbers with proportions for discrete categorical variables. Baseline continuous variables were compared between the 2 groups using the independent samples t-test and baseline discrete variables were compared using the chi-square test. Missing outcomes data were imputed in 2 steps.²³ First, a last-observation carry forward method was applied for subjects with nonmissing 3-month and 6-month scores, a previously validated imputation method in

SCI studies.^{23,29,30} Subsequently, a Markov chain Monte Carlo approach was used for remaining missing outcome data at 40 iterations.²³ The prerequisite missing-at-random assumption was accepted to be plausible based on literature finding losses to follow-up in SCI to be related to baseline demographic and injury factors, which was accounted for in the dataset.³¹ Predictive mean matching was used for continuous variables and logistic regression for discrete variables.

We used propensity score matching to identify cohorts of patients with similar baseline characteristics for the HEMI and LEMI groups.³² The propensity score was estimated with the use of multivariable logistic regression models with the mechanism of injury as the dependent variable and baseline variables that were significantly different between the 2 groups during descriptive analyses as covariates. A 1-to-1 nearest-neighbor matching protocol without replacement was used to match with a caliper width of 0.03 of the SD of the logit of the propensity score.³² Covariate balance between comparison groups as deemed adequate if below an absolute standardized mean difference (SMD) of 0.1. In the matched cohorts, comparisons of

outcomes were performed using a paired Student t-test for continuous variables, which was reported with mean differences (MDs) and p-values, and McNemar test for discrete variables, which was reported with proportions and p-values. A sensitivity analysis was conducted with a subgroup of patients from the NACTN registry and STASCIS trial with data on complications of shock (spinal, neurogenic, cardiogenic) and hypotension. These complications were included in a separate propensity score model as a covariate and outcomes were compared as mentioned above. All statistical analyses were performed using R, version 4.1.1, (The R Foundation for Statistical Computing, Vienna, Austria), at a significance level of 95% ($p < 0.05$; 2-sided).

RESULTS

1. Descriptive Statistics

A total of 2,452 acute traumatic SCI patients were identified in the combined dataset of 4 high-quality prospective, multicenter SCI databases (Fig. 1). After 1,785 patients were removed following the exclusion criteria, 667 patients were divided into 2

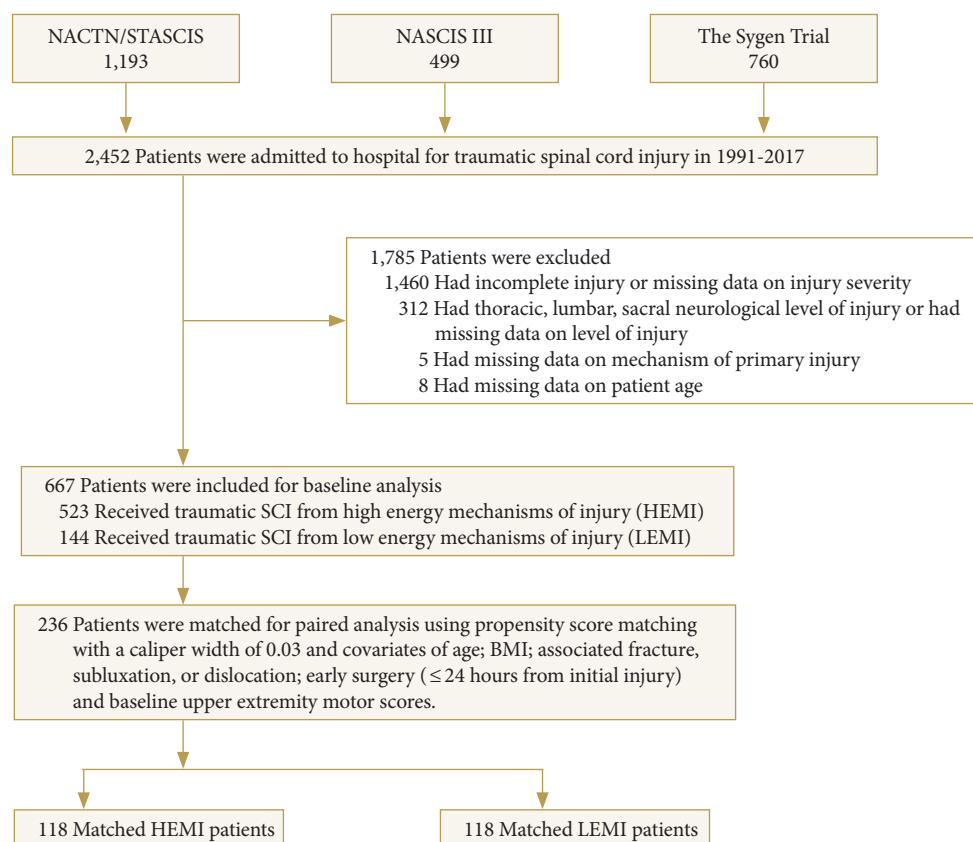


Fig. 1. Flowchart of study population. NACTN, North American Clinical Trials Network; STASCIS, Surgical Timing in Acute Spinal Cord Injury Study; NASCIS III, National Acute Spinal Cord Injury Study; SCI, spinal cord injury; BMI, body mass index.

groups: HEMI (n = 523, 78.4%) and LEMI (n = 144, 21.6%). Prior to propensity score matching, HEMI patients were generally younger (32.8 ± 13.5 years vs. 47.9 ± 17.9 years, $p < 0.001$) and had a greater proportion of patients with associated fractures, subluxations, and dislocations with their tSCI compared to LEMI patients (91.6% vs. 75.0%, $p < 0.001$). After admission, a greater proportion of LEMI patients received early surgical decompression ≤ 24 hours of initial injury (47.2% vs. 34.0%, $p = 0.005$). Descriptive statistics are detailed in Table 1.

2. Propensity Score Matching

The HEMI and LEMI groups were balanced with the covariates identified with a between-group difference threshold of $p < 0.1$: age, body mass index, baseline UEMS, early surgery, and associated fractures, subluxation, and dislocations. The match resulted in 118 pairs that were well balanced with an SMD of 0.1 or less for all variables (Table 1).

3. Primary Outcome

HEMI patients had a significantly worse motor recovery from baseline to follow-up based on their smaller change in upper extremity motor scores with a mean difference of 3.7 (12.0 ± 12.3 vs. 8.3 ± 12.0 , $p = 0.010$). Change in TMS (17.8 ± 19.6 vs. 11.9 ± 17.5 , $p = 0.011$) was significantly diminished in HEMI patients compared to LEMI patients with a mean difference of 5.9 (Table 2). We detected no significant differences between HEMI and LEMI patients on AIS grade conversion (LEMI: 41.5% vs. HEMI: 45.8%, $p = 0.609$) or change in LEMS (LEMI: 5.9 ± 12.6 vs. HEMI: 3.7 ± 9.6 , $p = 0.119$).

4. Sensitivity Analysis

In a subgroup of 1,193 patients from the NACTN registry and STASCIS trial, cardiovascular complications were included as a covariate in the propensity score match algorithm. From a total of 199 patients that met our inclusion and exclusion criteria, 90 patients were matched (Supplementary Table 1). After

Table 1. Descriptive statistics and between-group comparisons of LEMI and HEMI patients

Variable	Crude cohort			Propensity score-matched cohort		
	LEMI (n = 144)	HEMI (n = 523)	p-value	LEMI (n = 118)	HEMI (n = 118)	SMD
Age (yr)	47.9 ± 17.9	32.8 ± 13.5	$< 0.001^*$	42.7 ± 14.9	42.3 ± 15.4	0.026
Female sex	27 (18.8)	98 (18.7)	1.000	21 (17.8)	26 (22.0)	0.100
BMI (kg/m^2)	26.2 ± 4.8	25.4 ± 4.7	0.079	26.1 ± 4.9	26.0 ± 4.3	0.005
Fractures, subluxations, dislocations (%)	108 (75.0)	479 (91.6)	$< 0.001^*$	97 (82.2)	94 (79.7)	0.065
Early surgery rate (≤ 24 hr from initial injury) (%)	68 (47.2)	178 (34.0)	0.005^*	56 (47.5)	53 (44.9)	0.051
Baseline upper extremity motor score	11.5 ± 11.0	13.5 ± 12.7	0.088	12.4 ± 11.3	12.5 ± 11.5	0.009
Baseline lower extremity motor score	0 ± 0	0 ± 0	-	0 ± 0	0 ± 0	-
Baseline total motor score	11.6 ± 11.1	13.5 ± 12.7	0.104	12.4 ± 11.3	12.5 ± 11.5	0.004

Values are presented as mean \pm standard deviation or number (%).

HEMI, high-energy mechanism of injury; LEMI, low-energy mechanism of injury; BMI, body mass index; SMD, standardized mean difference.

* $p < 0.05$, statistically significant differences.

Table 2. Paired comparisons between matched HEMI and LEMI cohorts from propensity score matching

Outcome	Propensity score-matched cohort			
	LEMI (n = 118)	HEMI (n = 118)	Mean difference	p-value
Change in upper extremity motor score	12.0 ± 12.3	8.3 ± 12.0	3.7	0.010*
Change in lower extremity motor score	5.9 ± 12.6	3.7 ± 9.6	2.2	0.119
Change in total motor score	17.8 ± 19.6	11.9 ± 17.5	5.9	0.011*
≥ 1 AIS grade improvement (%)	49 (41.5)	54 (45.8)	-	0.609

Values are presented as mean \pm standard deviation or number (%).

HEMI, high-energy mechanism of injury; LEMI, low-energy mechanism of injury; AIS, American Spinal Injury Association Impairment Scale.

* $p < 0.05$, statistically significant differences.

paired analysis, the results of the sensitivity analysis supported our findings (Supplementary Table 2). Compared to LEMI patients, HEMI patients had a significantly decreased recovery of UEMS (12.7 ± 10.6 vs. 8.2 ± 8.2 , $p = 0.010$) and TMS (22.5 ± 25.1 vs. 13.2 ± 13.8 , $p = 0.025$).

DISCUSSION

To the best of our knowledge, this is the first study to thoroughly investigate the role of mechanism of injury in long-term neurological outcomes after acute traumatic complete cervical SCI.

Mputu et al. and others suggest that neural tissue destruction in high-energy trauma resulted in complete thoracic level injuries and this, coupled with resultant dislocation and shear injuries, caused poorer outcomes in high-energy injury patients, though they did not find mechanism of injury to be significantly associated with outcome.^{10,33,34} Much of the existing literature is based on supposed correlations such as the decrease in severity of injury overtime with the greater prevalence of falls, suggesting a possible correlation with energy of injury and outcome severity.^{10,35} Other studies comparing high-energy falls and MVCs to low-energy falls comment on the former causing complete injuries compared to the latter allowing us to predict that injury severity is often greater in HEMIs, with additional studies suggesting a lower quality of life resulting from a more severe mechanism of injury.^{7,36-39} Several studies have found that there are poorer outcomes in patients with higher injury mechanisms due to concomitant other injuries but do not clarify whether the outcome is directly related to the injury to the spine.^{7,34,40,41} Qiu et al.⁴² found that high-energy mechanisms were associated with motor complete injuries (in noncompression flexion injuries)—although they did not conduct a subgroup analysis consisting of only complete injuries, this allows us to deduce that perhaps the outcomes would also be more severe. While the aforementioned studies either allow for speculation on the impact of energy or have found there to be no bearing of energy of injury on outcome, our study demonstrates clear, significant, difference between HEMI and LEMI groups in motor recovery at follow-up.

Our primary outcomes included AIS grade conversion of at least 1 grade and change in constituent motor and sensory scores between baseline and follow-up. Although our analysis did detect a significant difference between groups in the composite AIS grade conversion, with more granularity, a significant difference in motor outcomes as revealed. Notably, we found that HEMI

patients had a significantly worse recovery TMS of an average of 5.9 points. Although minimum clinically important differences for neurological outcomes of acute traumatic SCI have not yet been established, motor recovery of even a single cervical segment could have significant impacts on a patient's independence in activities of daily living and quality of life. Our results suggest a diminished recovery in the upper extremity motor scores. This is clinically relevant as patients with tetraplegia often rate restoration of hand and arm motor function as their priority.^{43,44} The aforementioned findings refute a previous study's finding that the energy of initial trauma was not found to influence neurological outcome at 6-month follow-up in those with SCI.¹⁸ The previous study was limited to subgroup comparisons of less than 5 patients per group and defined high impact sports injuries as low-energy trauma. Another such study which did not see an impact on motor score was conducted by Dvorak et al.⁴⁵, who prospectively assessed factors impacting ASIA Motor Score, functional status, and quality of life – none of which were found to be impacted by mechanism or energy of injury. Kay et al.⁴⁶ studied the likelihood of walking at the time of discharge, which can be considered a surrogate for motor improvement, from rehab in various grade SCIs and found that ASIA C patients were more likely to walk than ASIA A or B, suggesting more severe grade results in worse long-term motor ability, allowing us to conclude this about HEMI compared to LEMI given that HEMIs are typically of higher grade. However, this was not studied specifically in the ASIA A group nor assessing the role of mechanism of injury, thus reinforcing the results of our group. Other studies have commented on higher energy falls resulting in ASIA A injuries, longer rehab stay and paraplegia, all outcomes in keeping with severe injury but no information regarding outcomes within one ASIA grade.⁴⁷ Similarly, Higashi et al.⁴⁸ did not find statistical significance in mechanism of injury and mortality across all grades of ASIA injury, however, they did not conduct a subgroup analysis for those only in the ASIA A cohort. There have been ample additional studies which comment on the lack of significant findings regarding the impact of mechanism/ etiology on outcomes.^{49,50} Our findings on motor recovery were supported by our sensitivity analysis that included complications of neurogenic, cardiogenic, and spinal shock as well as hypotension in a subgroup of patients from the NACTN registry and STASCIS trial.

Our study has several limitations. First, the combined dataset did not contain explicit granularity of data to differentiate falls based on height. Falls from high heights would be plausibly categorized as high-energy mechanisms of injury compared to falls

from low heights. A previous study found that patients with falls from greater heights resulted in more severe injuries and length of stay.⁴⁷ This may underestimate the effect size between the HEMI and LEMI groups. However, we make a point that in our database, most high-altitude falls are from workplace and sports-related activities such as climbing, so this categorization effect may be small, and our fundamental conclusions are supported. The older mean age of our LEMI cohort also aligns to that characteristic of low-height falls.⁴⁷ Future studies and registries should focus on recording the height of falls or the circumstances of falls, such as workplace injuries, which can be an indirect measure of a fall from high height. Another limitation of the study is its retrospective and nonrandomized nature. As our dataset is not randomized, we used propensity score matching to balance covariates between cohorts to create a quasi-experimental setting. Although this method can balance measured variables, unmeasured variables may be unbalanced between cohorts and may influence the results. These variables could include history of degenerative disc disease or spondylosis, which presents a focus for future studies. For future studies focusing on incomplete injuries, commentaries on the rates of central cord injury and incomplete cervical cord injury without fracture may indirectly measure the impact of degenerative disc disease and cervical spondylosis.

CONCLUSION

Our work presents a comprehensive analysis of the role of mechanism of injury on the long-term neurological recovery of complete cervical tSCI patients. Our findings suggest that patients with a HEMI, such as those from MVCs or sports, may have significantly lower motor recovery at one year compared to those that sustained tSCIs from falls. Future studies may choose to explore larger cohorts, changes in outcomes within ASIA B, C, and D, and specific function outcomes such as ambulating, eating, and writing. Similar to our findings, increasing literature is supporting the heterogeneity of outcomes following complete tSCI. To provide more precise care to these patients, mechanism of injury should be considered in efforts to prognosticate and understand the patient recovery trajectory.

NOTES

Supplementary Materials: Supplementary Tables 1-2 can be found via <https://doi.org/10.14245/ns.2244518.259>.

Supplementary Table 1. Descriptive statistics and between-

group comparisons of LEMI and HEMI patients in sensitivity analysis subgroup.

Supplementary Table 2. Paired comparisons between matched HEMI and LEMI cohorts from propensity score matching of sensitivity analysis subgroup.

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Supplementary Table 1. Descriptive statistics and between-group comparisons of LEMI and HEMI patients in sensitivity analysis subgroup

Variable	Crude cohort			Propensity score-matched cohort			
	LEMI (n = 67)	HEMI (n = 132)	p-value	LEMI (n = 45)	HEMI (n = 45)	p-value	SMD
Age (yr)	55.07 ± 15.76	38.66 ± 15.02	< 0.001*	48.49 ± 14.22	47.96 ± 16.16	0.868	0.035
BMI (kg/m ²)	27.91 ± 5.42	26.13 ± 5.50	0.032	27.52 ± 5.46	25.94 ± 6.42	0.212	0.265
Female sex	18 (26.9)	23 (17.4)	0.170	11 (24.4)	14 (31.1)	0.638	0.149
Fractures, subluxations, dislocations	42 (62.7)	69 (52.3)	0.212	28 (62.2)	29 (64.4)	1.000	0.046
Early surgery rate (≤ 24 hr from initial injury)	42 (62.7)	85 (64.4)	0.936	30 (66.7)	32 (71.1)	0.820	0.096
Baseline upper extremity motor score	11.69 ± 10.86	13.19 ± 12.06	0.392	12.64 ± 11.33	12.69 ± 12.50	0.986	0.004
Baseline lower extremity motor score	0.00 ± 0.00	0.00 ± 0.00	-	0.00 ± 0.00	0.00 ± 0.00	-	< 0.001
Baseline total motor score	11.44 ± 10.75	13.19 ± 12.06	0.320	12.64 ± 11.33	12.69 ± 12.50	0.986	0.004
Complications							
Spinal shock	17 (25.4)	72 (54.5)	< 0.001*	17 (37.8)	20 (44.4)	0.668	0.136
Neurogenic shock	18 (26.9)	63 (47.7)	0.007*	16 (35.6)	16 (35.6)	1.000	< 0.001
Cardiogenic shock and hypotension	22 (32.8)	62 (47.0)	0.079	18 (40.0)	17 (37.8)	1.000	0.046

Values are presented as mean ± standard deviation or number (%).

HEMI, high-energy mechanism of injury; LEMI, low-energy mechanism of injury; BMI, body mass index; SMD, standardized mean difference.

*p < 0.05, statistically significant differences.

Supplementary Table 2. Paired comparisons between matched HEMI and LEMI cohorts from propensity score matching of sensitivity analysis subgroup

Outcome	LEMI (n = 45)	HEMI (n = 45)	Mean difference	p-value
Change in upper extremity motor score	12.7 ± 10.6	8.2 ± 8.2	4.5	0.010*
Change in lower extremity motor score	9.8 ± 16.4	5.0 ± 10.4	4.8	0.104
Change in total motor score	22.5 ± 25.1	13.2 ± 13.8	9.3	0.025*
≥ 1 AIS grade improvement (%)	27 (60.0)	30 (66.7)	-	0.606

Values are presented as mean ± standard deviation or number (%).

HEMI, high-energy mechanism of injury; LEMI, low-energy mechanism of injury; AIS, American Spinal Injury Association Impairment Scale.

*p < 0.05, statistically significant differences.