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Secondary Complications in Pediatric Traumatic Spinal Cord Injury: A Systematic Review

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Abstract **Objectives: Background:** Pediatric traumatic Spinal Cord Injury (SCI) is a rare but profoundly disabling medical disorder with a high prevalence of secondary complications, which significantly impede long-term functional and developmental achievement. Although they are of clinical importance, current evidence on the patterns, severity, risk factors and treatment of these complications in pediatric SCI is piecemeal and variable in reporting. **Method:** A systematic review was conducted based on PRISMA 2020 standards, solely on nonrandomised observational studies that documented secondary complications in individuals aged 21 years and below with traumatic Spinal Cord Injury (SCI). Exhaustive searches were conducted in seven databases with Boolean operators and MeSH terms. Data extraction was carried out as per a preconceived protocol and study quality was evaluated using the ROBINS-I tool. The outcome measured was prevalence rates, measure of severity, risk factors and prevention or management of the reported complications. Certainty of the evidence was evaluated using the GRADE approach. **Results:** Nine eligible studies involving a total sample of more than 3000 pediatric patients were included. Neurogenic bladder showed the highest prevalence (91.2%), followed by urinary incontinence (69.8%), constipation (72.1%), spasticity (57%), pressure ulcers (20.4–57.3%) and UTIs (11.6-74%). Pain (69%), scoliosis (40-82%) and autonomic dysreflexia (19.7-42%) were also common. Odds ratios showed significant associations between cervical or complete injury and risk increase for UTIs (OR: 1.05–1.09), autonomic dysreflexia (OR: 1.08-1.09) and respiratory complications (OR: 1.09-1.16). Qualitative synthesis revealed that early assessment intervals ranged from acute hospitalization to more than 28 years after injury. Interventions used were catheterization training, early rehabilitation, surgical decompression, spasticity management and caregiver education. Risk factors like young age at injury, higher level of injury, completeness of neurological injury and non-compliance of families were found to be consistently associated with unfavorable outcomes. **Conclusion:** Synthesis of evidence revealed the prevalence and multicausal aetiology of paediatric traumatic SCI secondary complications. Inconsistencies between studies were revealed with evidence for early detection, longitudinal follow-up and person-centred interventions to prevent long-term morbidity. The findings also revealed a call for the urgent creation of age-sensitive assessment tools and paediatric-specific clinical guidelines to maximise care and reduce complication-related disability among the paediatric population.

Key Words Pediatric Spinal Cord Injury, Secondary Complications, Neurogenic Bladder, Pressure Ulcers, Urinary Tract Infections, Spasticity, Scoliosis, Autonomic Dysreflexia, Observational Studies, Rehabilitation, Catheterization, Risk Factors

INTRODUCTION

Traumatic Spinal Cord Injury (SCI) in children represents a heterogeneous and complex condition that is associated with serious lifelong morbidity, functional impairment and significant healthcare expenditure. The worldwide prevalence of pediatric SCI is relatively lower than that seen in adults, but the ensuing clinical consequences have significant repercussions due to the disruption of uninterrupted growth, neuromuscular development and psychosocial maturation in injured children and adolescents [1]. Pediatric SCI can be attributed to a range of causes, including motor vehicle collisions, falls, sports injury and cases of non-accidental trauma, with varying epidemiological patterns on the basis of geographical and socioeconomic factors [2]. Because of anatomical and physiological properties inherent in the developing spine, children exhibit susceptibility to unique mechanisms of injury, including Spinal Cord Injury without Radiographic Abnormality (SCIWORA), which complicates diagnosis and prediction [3].

Following the initial mechanical injury, a cascade of secondary pathophysiologic events is triggered, which contribute significantly to the perpetuation of neural tissue injury and the genesis of systemic consequences. The scope of these secondary complications is broad-based, crossing a wide range of clinical disorders, among them, but not limited to, neurogenic bladder dysfunction, recurrent UTI, pressure sores, respiratory complications, spasticity, autonomic dysreflexia, gastrointestinal dysmotility, musculoskeletal deformities (e.g., scoliosis), pain disorders and psychological disturbances [4,5]. Their frequency and severity are dependent on a range of factors, including level of the neurological damage, completeness of the damage, age at damage, duration since damage and co-morbid disease [6]. These complications not only threaten functional rehabilitation but also contribute significantly to enhanced healthcare utilization, rates of hospital readmission and burden of caregiving and thus highlight the importance of careful multidisciplinary observation and targeted interventions [7].

In spite of the acknowledged secondary complication burden in children with SCI, existing clinical data are heterogeneous, mostly retrospective or observational in nature and often marred by heterogeneity in outcome definitions, assessment modalities and reporting measures. In contrast to the adult population, where systematic clinical guidelines and strong longitudinal data drive preventive and management interventions, pediatric SCI care is currently based on under-representation in clinical studies and absence of age-specific guidelines [8]. This absence of child-specific evidence is compounded further by methodological deficiencies, small sample size and exclusion of children from large SCI trials, thus restricting generalizability to this vulnerable population [9].

A variety of multidisciplinary interventions, including urological follow-up, rehabilitation treatment, orthopedic surveillance, respiratory management and psychosocial counseling, have been proposed for prevention of complications but their relative efficacy, timeliness of initiation and long-term outcomes are not well established in pediatric patients [10]. To fill these gaps, the present systematic review aims to summarize the existing evidence base to identify the most frequently reported secondary complications in children and adolescents with traumatic spinal cord injury, evaluate their temporal and clinical characteristics and evaluate current preventive and management strategies.

MATERIALS AND METHODS

Eligibility Criteria

The PECOS framework was constructed in compliance with PRISMA 2020 reporting standards [11]. All elements of the eligibility criteria were thoroughly matched with the PRISMA checklist to guarantee that reproducible study choice, systematic examination and precise documentation of the inclusion rationale were achieved. The Population (P) was children and adolescents under the age of 21 years diagnosed with traumatic SCI. The Exposure (E) was traumatic spinal cord injuries resulting from a range of causes, including motor vehicle collisions, falls, sports trauma, or non-iatrogenic penetrating trauma. The Comparator (C) was not required due to the descriptive nature of the review; however, where possible, it involved comparisons with children with no secondary complications or certain subgroups stratified by injury level or completeness.

The Outcomes (O) were the types, frequencies, severities, risk factors and management approaches for secondary complications, including but not limited to, pressure ulcers, urinary tract infections, respiratory complications, spasticity, scoliosis, autonomic dysreflexia and neuropathic pain. The study design (S) was nonrandomized observational study designs such as cohort studies, case-control studies, cross-sectional studies and registry-based studies and not Randomized Controlled Trials (RCTs) since conducting RCTs on pediatric traumatic spinal cord injury is both ethically and practically difficult, primarily due to the low frequency, heterogeneity of the types of injury and the complexity of secondary complications that occur over extended periods. Observational studies therefore turned out to be the most ethically sound and scientifically practical means of gathering clinical data to examine patterns of complications and management results in this group.

Inclusion and Exclusion Criteria

The inclusion criteria for this systematic review were original research studies that (1) recruited pediatric patients aged less than 21 years who had traumatic spinal cord injury, (2) investigated secondary complications including pressure ulcers, urinary tract infections, respiratory complications, spasticity, scoliosis, autonomic dysreflexia, pain, constipation, or neurogenic bladder, (3) had quantitative or qualitative data on the prevalence, severity, risk factors, or interventions for these complications and (4) employed observational study designs, including retrospective and prospective cohort studies, cross-sectional analysis, or case-control designs. Peer-reviewed journal articles published between 2000 and 2024 and written in English were deemed suitable for analysis.

Exclusion criteria were (1) patient age above 21 years in studies, (2) non-traumatic spinal cord injury studies, e.g., congenital, iatrogenic, or tumor-related spinal injury, (3) case reports, editorials, reviews, conference abstracts, or animal studies and (4) studies with no documentation of secondary complications or outcomes not relevant to the review's interest, i.e., primary neurological recovery or surgery without complication data.

Database Search Protocol

A systematic electronic search was conducted in seven separate databases-PubMed, Embase, Web of Science, Scopus, Cochrane Library, CINAHL and Google Scholar- to find all potentially relevant studies. Boolean operators and MeSH terms were altered to each database's syntax.

Table 1: Search strings assessed across each database

Database	Search String
PubMed	("pediatric"[MeSH Terms] OR "child"[MeSH Terms] OR "adolescent"[MeSH Terms]) AND ("spinal cord injuries"[MeSH Terms] AND "trauma"[All Fields]) AND ("secondary complications"[All Fields] OR "pressure ulcer"[MeSH Terms] OR "urinary tract infections"[MeSH Terms] OR "spasticity"[MeSH Terms] OR "autonomic dysreflexia"[MeSH Terms] OR "scoliosis"[MeSH Terms] OR "pain"[MeSH Terms])
Embase	('pediatric'/exp OR 'child'/exp OR 'adolescent'/exp) AND ('spinal cord injury'/exp AND 'trauma'/exp) AND ('secondary complication'/exp OR 'pressure ulcer'/exp OR 'urinary tract infection'/exp OR 'respiratory complication'/exp OR 'spasticity'/exp OR 'autonomic dysreflexia'/exp OR 'pain'/exp)
Scopus	(TITLE-ABS-KEY ("pediatric" OR "child" OR "adolescent") AND TITLE-ABS-KEY ("traumatic spinal cord injury") AND TITLE-ABS-KEY ("secondary complications" OR "pressure ulcers" OR "urinary tract infections" OR "autonomic dysreflexia" OR "spasticity" OR "scoliosis" OR "pain"))
Web of Science	TS=(pediatric OR child OR adolescent) AND TS=(traumatic spinal cord injury OR TSCI) AND TS=(pressure ulcers OR spasticity OR respiratory complications OR scoliosis OR autonomic dysreflexia OR pain)
Cochrane Library	(pediatric OR child OR adolescent) AND (spinal cord injury AND trauma) AND (secondary complications OR pressure ulcers OR urinary tract infections OR respiratory complications OR autonomic dysreflexia OR spasticity)
CINAHL	(MH "Pediatric Patients") AND (MH "Spinal Cord Injuries") AND (secondary complications OR pressure ulcers OR urinary tract infections OR respiratory issues OR spasticity OR pain OR scoliosis)
Google Scholar	allintitle: pediatric traumatic spinal cord injury secondary complications pressure ulcers spasticity scoliosis urinary infections pain

The terms used were: "pediatric" OR "child" OR "adolescent" AND "traumatic spinal cord injury" OR "TSCI" AND "secondary complications" OR "pressure ulcers" OR "urinary tract infections" OR "respiratory complications" OR "spasticity" OR "scoliosis" OR "autonomic dysreflexia" OR "neuropathic pain". Database-specific filters were used to exclude animal studies and limit results to human participants and articles published between the years 2000 and 2024 (Table 1).

Data Extraction Protocol

Data were independently extracted by two reviewers utilizing a pre-established data extraction form designed for this review. Items to be extracted included study identifiers (first author, year, country), study design, sample size, demographic distribution by age and sex, description of Spinal Cord Injury (SCI) by level, etiology and completeness, time since injury at assessment, types of secondary complication described, diagnostic criteria, rates of incidence or prevalence, indices of severity, reported risk factors and preventive or therapeutic interventions. Where discrepancies arose between reviewers, these were resolved through discussion or referral to a third reviewer.

Bias Assessment Protocol

The risk of bias in each study was evaluated using the ROBINS-I instrument [12]. Each study was reviewed in seven domains: Confounding bias, participant selection, classification of the intervention, deviations from intended interventions, omission of data, outcome measurement and selection of reported outcomes. Each domain was assigned a rating of low, moderate, serious, or critical risk of bias. The final bias determination was made using these ratings. These ratings were performed by independent reviewers and, if necessary, reached consensus regarding how to address any discordance.

Certainty Bias Assessment

GRADE approach [13] (Grading of Recommendations Assessment, Development and Evaluation) was used to establish the overall confidence in the evidence for each outcome based on the data collected. Because of the use of non-randomized designs, the initial certainty level was set at low. The certainty level was then downgraded with the presence of risk of bias (as assessed by ROBINS-I), inconsistency, indirectness, imprecision, or publication bias if such existed. Nevertheless, in accordance with those studies with large effect sizes or dose-response associations, upgrading was a possibility. The final certainty ratings were graded as high, moderate, low, or very low.

RESULTS

Literature searching produced 836 bibliographic records (Figure 1). Following automated de-duplication (n = 42), 794 titles and abstracts were screened initially. All records screened were potentially relevant and were hence searched for full-text retrieval; however, 28 full texts were not available, leaving 766 articles to be assessed for eligibility. Full-text assessment ruled out 757 articles-case reports (n = 186), animal studies (n = 234), narrative or systematic reviews (n = 171) and studies out of scope of secondary complications in paediatric traumatic spinal cord injury (n = 166). Nine studies [14-22] thus m*et al*l inclusion criteria.

Bias Levels Assessed

Risk-of-bias assessment with the ROBINS-I tool identified generally moderate overall risk throughout the evidence base (Figure 2). Confounding was low in five studies [14,16,17,19,21] and moderate in four [15,18,20,22]. Participant selection was low in all studies except two cohorts with moderate concerns [14,19]. Intervention classification and deviation domains were low in all studies, whereas missing-data bias was moderate in three reports [14,20] but low in the others. Outcome-measurement bias was moderate in four studies [16,20–22] due to non-blinded measurement or self-report use, but selective-reporting bias was low in four studies and moderate in two [17,18].

Demographic Variables Assessed

The population profile presented in Table 2 shows a global heterogeneous patient population recruited from several pediatric traumatic SCI retrospective and observational studies.

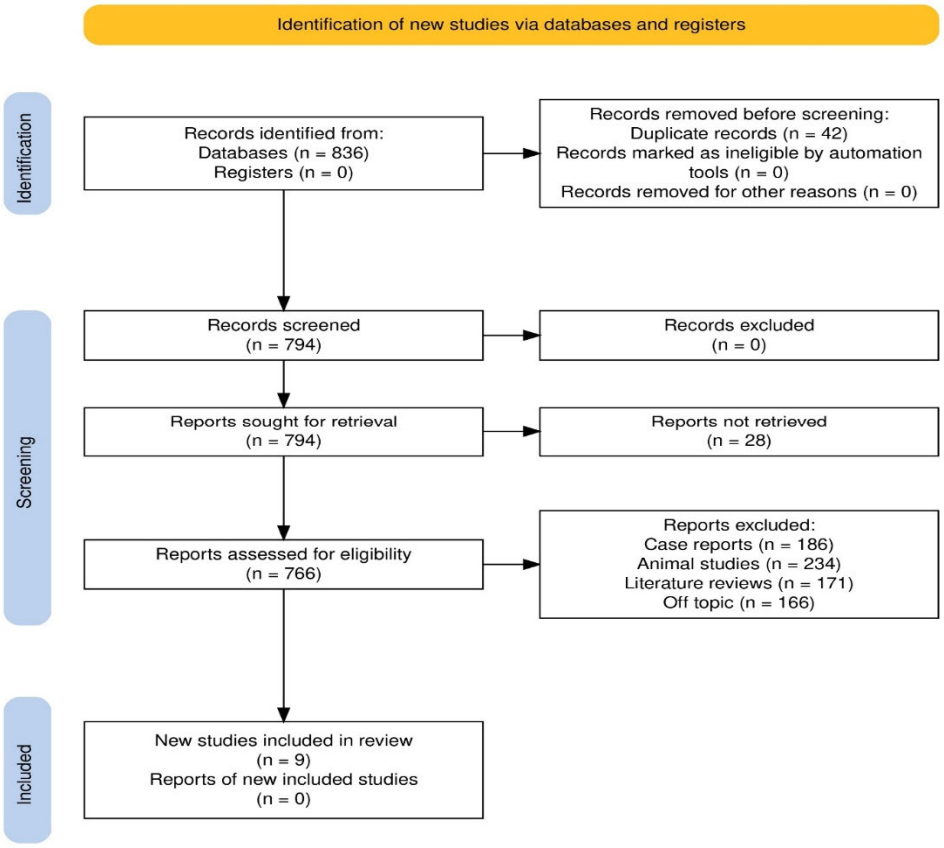

Figure 1: Article Selection Process for the Review

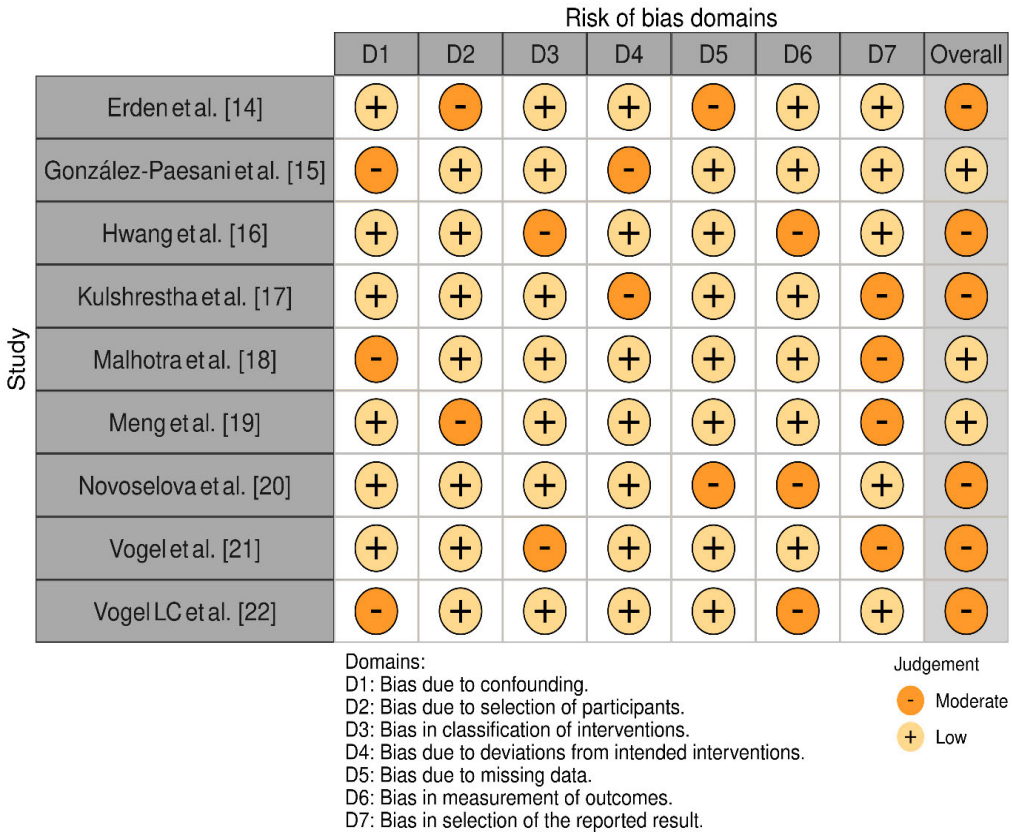

Figure 2: Bias Assessment using the ROBINS-I tool

Table 2: Demographic Variables Assessed

Author ID	Year	Location	Study Design	Sample Size	Mean Age (Years)	Male: Female Ratio	Follow-up Period
Erden *et al.* [14]	2023	Turkey	Retrospective observational	147	13.6±4.19	73.5% male	11.17±20.80 months
González-Paesani *et al.* [15]	2018	Spain	Observational cohort	Not reported	Not reported	Not reported	Acute hospitalization
Hwang *et al.* [16]	2014	USA, Canada	Longitudinal observational	351	13.8±3.6	64.4% male	Median 5.1 years
Kulshrestha *et al.* [17]	2020	UK	Retrospective longitudinal review	62	Median: 17	71% Male	Median 28 years
Malhotra *et al.* [18]	2023	Canada/USA	Multicenter observational cohort	1853	Not explicitly reported	Not explicitly reported	In-hospital
Meng *et al.* [19]	2023	China	Retrospective follow-up	86	Median: 6.2	10.5% male	3–130 months
Novoselova *et al.* [20]	2020	Russia	Retrospective cohort	167	11.4±4.0	56.3% male	Up to 3 years
Vogel *et al.* [21]	2002	USA	Structured interview cohort	216	14.1	69% Male	Mean 14.2 years
Vogel *et al.* [22]	2002	USA	Structured interview cohort	216	14.1	69% Male	Mean 14.2 years

Table 3: Technical Characteristics Assessed

Author ID	Groups Assessed	Level and Completeness of SCI	Time Since Injury at Assessment	Type of Secondary Complication Assessed	Assessment Tools/Diagnostic Criteria	Incidence/Prevalence Rate (%)	Severity Grading/Outcome Measure	Risk Factors Identified	Preventive/Management Interventions Applied	Conclusion Assessed
Erden *et al.* [14]	Cervical, Thoracic, Lumbar	Complete (65%), incomplete	Mean 11.17 months (0.5-240)	Neurogenic bladder (91.2%), spasticity (41.54%), neuropathic pain (29.3%)	AIS scale, urodynamics, FAC scale	Neurogenic bladder (91.2%), UTIs (11.6%), pressure ulcers (20.4%)	AIS and FAC classification	Young age, level of injury	Regular follow-ups, neurogenic bladder management, pain control	Prevention and early management crucial
González-Paesani *et al.* [15]	Single cohort	Not explicitly detailed	Acute hospitalization	Respiratory complications	Clinical & respiratory assessment	Not explicitly stated	Not explicitly reported	Level of injury severity	Acute clinical management strategies	Early identification important
Hwang *et al.* [16]	Four ASIA groups (C1-4, C5-8, T1-S5, AIS D)	Mixed completeness	Median interval 5.1 years	UTIs, pressure ulcers, autonomic dysreflexia, spasticity, respiratory issues	Clinical diagnosis, structured questionnaires	Severe UTI (OR 1.05–1.09), autonomic dysreflexia (OR 1.08–1.09), respiratory issues (OR 1.09–1.16)	Odds ratios, longitudinal tracking	Injury severity, aging, level of injury	Preventive care, annual monitoring	Longitudinal follow-up critical
Kulshrestha *et al.* [17]	Traumatic and Neurological SCI	Not explicitly reported	Median follow-up 28 years	Scoliosis	Clinical, Radiological Cobb angle	82% traumatic injury	ROC Curve for prediction (AUC 0.83)	Younger age at injury	Physiological management, bed rest	Age <14.6 years predictor for scoliosis
Malhotra *et al.* [18]	Cervical & Thoracic SCI	Cervical complete/incomplete, Thoracic complete/incomplete	In-hospital	Pressure ulcers, pneumonia, cardiac arrest, VAP	ACS TQIP criteria	Pressure ulcers, pneumonia frequent (specific % not provided)	ACS-defined major adverse events	Cervical complete injury, severe abdominal injuries, GCS <13	Surgical decompression, immobilization	High morbidity; cervical injuries critical for AE
Meng *et al.* [19]	Complete & Incomplete SCI	Thoracic (91.9%), Lumbar	Median 38 months (3–130)	Spasticity (18.6%), urinary incontinence (69.8%), pressure ulcers (20.9%), constipation (72.1%)	AIS scale, clinical assessment	Spasticity (18.6%), pressure ulcers (20.9%)	AIS impairment scale	Complete injury, higher spinal level	Comprehensive rehab, catheterization training	Comprehensive rehab essential
Novoselova *et al.* [20]	Group I & II	Tetraplegia, Paraplegia	Admission, 6 months, 1, 3 years	Pressure ulcers, UTIs, autonomic dysreflexia, psychoemotional disorders	ASIA, Weiss scale, Ashworth scale, questionnaires	Pressure ulcers (57.3%), UTIs (54.1%), autonomic dysreflexia (19.7%)	Severity using ASIA, grading of ulcers (Stage I–IV)	Family non-compliance, lack of parental control	Early rehab, telemedicine monitoring, parent education	Early intervention reduces complication frequency
Vogel *et al.* [21]	Paraplegia, Tetraplegia	Tetraplegia 57%, Paraplegia 43%	Mean 14.2 years	Pain, spasticity, scoliosis, hip contracture	ASIA scale, clinical questionnaire	Pain (69%), spasticity (57%), scoliosis (40%)	ASIA Motor score, functional assessment	Age, duration of injury, level of injury	Medication for spasticity, orthopedic management	Long-term musculoskeletal complications common
Vogel *et al.* [22]	Paraplegia, Tetraplegia	Tetraplegia 57%, Paraplegia 43%	Mean 14.2 years	UTI, bowel incontinence, autonomic dysreflexia	Clinical questionnaire, FIM scores	UTI (74%), bowel incontinence (63%), dysreflexia (42%)	Clinical severity, hospitalization rates	Neurological impairment, functional limitation	Bladder/bowel management, caregiver training	Frequent urologic and autonomic complications

The time frame of these studies ranges from 2002 [21,22] to 2023 [14,18,19] and shows consistent academic interest and heterogeneous chronological spread. These studies were conducted in several countries, including Turkey [14], Spain [15], the United States and Canada [16,18,21,22], the United Kingdom [17], China [19] and Russia [20].

In terms of study design, retrospective observational methods were the most common, represented by retrospective observational [14], retrospective longitudinal [17], retrospective follow-up [19] and retrospective cohort designs [20]. Observational cohorts [15] and longitudinal observational studies [16] were also represented and structured interview cohort methods were mentioned twice [21,22].

Sample sizes reported through these studies varied widely from fairly small populations, e.g., 62 United Kingdom participants [17] and 86 Chinese participants [19], to large populations of 351 participants assessed in the United States and Canada [16].

Table 4: GRADE Assessment Observations

Study Design Group	Number of Studies	Common Reported Finding	Risk of Bias	Consistency of Results	Applicability to Population	Precision of Estimates	Other Considerations	Overall Certainty Rating
Retrospective Observational and Cohort (Erden *et al.* [14], Meng *et al.* [19], Novoselova *et al.* [20])	3	Early rehabilitation and management reduces complication frequency	Low to Moderate	Consistent	Direct	Moderate	None	Moderate
Observational Cohort - Acute Hospitalization (González-Paesani *et al.* [15], Malhotra *et al.* [18])	2	High acute-phase morbidity, especially in cervical injuries	Low to Moderate	Consistent	Direct	Low	None	Low
Longitudinal Observational (Hwang *et al.* [16], Kulshrestha *et al.* [17])	2	Longitudinal monitoring essential for predicting and mitigating complications	Low	Consistent	Direct	Moderate	None	Moderate
Structured Interview Cohort (Vogel *et al.* [21], Vogel *et al.* [22])	2	Chronic musculoskeletal, autonomic, and urologic complications common	Low	Consistent	Direct	Moderate	None	Moderate

There were also very large datasets of 1853 patients from multicenter assessments carried out in the United States and Canada [18]. Intermediate sample sizes were provided by 147 Turkish patients [14], 167 Russian participants [20] and homogeneous populations of 216 patients recruited into structured interview-based studies from the United States [21,22].

Mean participant ages also differed, in general accordance with pediatric to adolescent age range common in traumatic SCI research. Mean ages varied as low as median 6.2 years in China [19] to median 17 years in the UK [17], corresponding to wide pediatric age coverage. Other studies ranged similarly in a corresponding adolescent age range, e.g., 11.4±4.0 years in Russia [20], 13.6±4.19 years in Turkey [14] and approximately 14.1 years in USA-based structured cohorts [21,22]. Mean ages were not reported in observational cohorts in Spain [15] and multicenter observational cohorts in Canada and USA [18].

Male-to-female ratios reported in different studies produced a consistent predominance of male populations, with males consistently outnumbering females in rate of occurrence. The Turkish retrospective observational cohort reported the highest percentage of males at 73.5% [14], followed by the United Kingdom at 71% [17] and both structured interview cohorts in the USA at 69% [21,22]. The lowest percentage of males was, however, seen in China, where males made up just 10.5% of the population [19], showing a vast disparity with all other geographic regions. Intermediate percentages of males were seen in Russia at 56.3% [20] and North American longitudinal observational cohorts at 64.4% [16]. This predominance of males is largely consistent with established epidemiological patterns in traumatic SCI.

The follow-up intervals reported in various studies reflected significant heterogeneity that was reflective of various research aims. For instance, lengths of acute hospitalizations were reported in Spain [15] and in-patient observation periods were reported in North American multicenter studies [18]. Long-term longitudinal follow-ups were also reported, with median durations of up to 28 years in the United Kingdom [17]. Intermediate follow-up periods were also commonly reported, such as a median of 5.1 years in North America [16], up to 3 years in Russia [20] and a mean of 14.2 years in United States structured interview cohorts [21,22]. A mean follow-up period of 11.17±20.80 months was also reported in Turkey [14], while China reflected a broad follow-up duration of 3 to 130 months [19].

Evaluated Cohorts

The groups under the selected studies (Table 3) showed extensive heterogeneity across the studies, including complete and incomplete cervical, thoracic and lumbar SCI [14,18,19] and well-defined cohorts defined by ASIA classifications from cervical (C1-C8) to thoracic-lumbar (T1-S5) injuries and AIS-D classifications [16]. Additionally, specific categories were clarified that included both tetraplegia and paraplegia [20–22]. Other studies were single-cohort designs for respiratory complications [15] and comparative studies investigating differential effects of traumatic and neurological SCI etiologies [17], thus offering wide representation and increasing the potential to generalize the findings.

Level and Degree of SCI

Completeness and scope of SCI evaluated in these studies were highly heterogeneous. While some studies explicitly detailed the completeness of injury, with most of the injuries (65%) being complete in Turkey [14] and the completeness rates of thoracic injuries (91.9%) in China [19], others reported mixed or partially detailed evaluations like cervical and thoracic SCI cases with mixed completeness status from Canada/USA [18] and mixed completeness with tetraplegia and paraplegia from Russia [20]. Two studies showed clearly defined distributions with tetraplegia accounting for 57% and

paraplegia for 43% of their sample populations [21,22]. Other studies failed to clearly detail the completeness of injury [15,17], which narrowed direct comparability of all findings.

Duration since Injury at Evaluation

The follow-up intervals after injury were extremely heterogeneous, ranging from the acute phases of hospital stay [15] to intermediate follow-up intervals averaging approximately 11.17 months in Turkey [14], 38 months in China [19] and median follow-up of 5.1 years in North American cohorts [16]. In addition, ancillary studies extended the time period by following patient outcomes for median follow-up intervals ranging up to 28 years in the United Kingdom [17] and mean durations up to 14.2 years in the United States [21,22]. Some studies also provided sequential assessment at multiple follow-up intervals, including admission, 6 months, 1 year and up to 3 years post-injury in Russia [20], thus facilitating easier understanding of longitudinal evolution of complications. A multicenter observational cohort, on the other hand, only studied in-hospital durations [18], focusing on immediate secondary complications noted within the acute time period.

Type of Assessed Secondary Complication

Research has widely studied some secondary complications, including most prominently neurogenic bladder (91.2%), spasticity (41.54%) and neuropathic pain (29.3%) in Turkey [14]. Furthermore, North American research noted Urinary Tract Infections (UTIs), pressure ulcers, autonomic dysreflexia and respiratory complications [16,18,22] and scoliosis was researched in the United Kingdom [17]. In Russia, psychoemotional disorders and physical complications including UTIs, autonomic dysreflexia and pressure ulcers were an area of priority [20]. Incidence of pain, spasticity, scoliosis and hip contractures was reported in several studies [21]. One particular study examined respiratory complications in the acute stage of hospitalization in Spain [15], thus highlighting the vast spectrum of medical complications of pediatric Spinal Cord Injury (SCI).

Evaluation Tools/Diagnostic Criteria

The assessment methods employed were both extensive and stringently standardized, including the American Spinal Injury Association (ASIA) impairment scale, which has been extensively used in studies originating from Turkey, China, Russia and the USA [14,19-21]. Other parameters included structured clinical questionnaires and Functional Independence Measure (FIM) scores, particularly in the USA [22]. In the UK, radiological measurements with the Cobb angle were regarded as the gold standard for measuring scoliosis [17]. The Trauma Quality Improvement Program (ACS TQIP) criteria were used in studies in Canada and the USA to determine complications during hospitalization [18]. Other studies also relied extensively on clinical and respiratory assessment [15] and on the Weiss and Ashworth scales for evaluating muscular and neurological functions [20], as well as on urodynamic tests used to determine neurogenic bladder complications [14], thereby showing an extensive range of validated clinical assessment tools.

Incidence/Prevalence Rate (%)

The secondary complication reported prevalence and incidence rates are highly variable. For instance, Turkey reported high prevalence of neurogenic bladder (91.2%) as well as high incidence of urinary tract infections (UTIs) (11.6%) and pressure ulcers (20.4%) [14]. Similarly, China reported high prevalence of spasticity (18.6%), urinary incontinence (69.8%), pressure ulcers (20.9%) and constipation (72.1%) [19]. North American research also provided quantitative results with the presentation of respective odds ratios for severe UTIs (OR: range 1.05-1.09), autonomic dysreflexia (OR: range 1.08-1.09) and respiratory complications (OR: range 1.09-1.16) [16]; further findings reported that UTIs (74%), bowel incontinence (63%) and autonomic dysreflexia (42%) were significant clinical issues [22]. Other research also uniformly provided high prevalence rates, including pain (69%), spasticity (57%) and scoliosis (40%) in United States populations [21] and high rates of pressure ulcers and pneumonia, though percentages were not available in Canada or the USA [18].

Severity Grading/Outcome Measure

Severity grading and outcome measures used were AIS and FAC classifications to detect neurological and functional disability in Turkey [14], use of the AIS impairment scale in China [19], ROC curve analyses to predict scoliosis with AUC 0.83 in the UK [17] and standardized clinical and hospitalization rates based on structured questionnaires and FIM scores in the USA [22]. Of notable mention, odds ratios were leading statistical indicators for quantifying severity and probability of secondary complications in the USA and Canada [16], while ACS-defined major adverse events provided a reproducible gold standard in multicenter studies [18]. ASIA motor scores and functional assessment were consistently the indicators of neurological and functional outcomes [21], while pressure ulcer grading (Stage I-IV) and severity based on the ASIA classification were widely used in Russia [20].

Risk Factors Identified

The studies reviewed revealed some of the most significant risk factors for the development of secondary complications. Younger age at injury was found to be an important predictor for the development of scoliosis in UK populations [17], while complete injuries and higher levels of the spine posed considerably increased risks for complications in Turkish and Chinese populations [14,19]. Family compliance and parental control were found to be causative factors in Russia [20] and severe neurological impairments and limitations in function impacted secondary complications such as UTIs, bowel incontinence and autonomic dysreflexia in USA populations [22]. Cervical complete injury, harsh abdomen trauma and GCS <13 were significant risks for severe in-hospital adverse events in Canada/USA [18].

Preventive/Management Interventions Used

Prevention and management interventions suggested in these studies were complete rehabilitation protocols, such as catheterization and bladder management education [14,19,22], drug and orthopedic contracture and spasticity management [21], physiological management and prolonged bed rest regimes for prevention of scoliosis [17] and follow-up visits with a focus on pain management regimes [14]. Preventive care, yearly monitoring and early rehabilitation through telemedicine technologies were suggested as novel interventions [16,20], but surgical decompression and immobilization were still critical acute-phase interventions [18].

Certainty Assessment Observations

The GRADE assessment of certainty indicated that retrospective cohort and observational studies [14,15,19,20] possessed moderate evidence certainty when combined (Table 4). The studies identified early intervention, management of neurogenic bladder and spasticity control as being required in avoiding secondary complication effects. The risk of bias in this category was approximated to be low to moderate with findings being mostly concordant, directly applicable to pediatric spinal cord injury populations and having demonstrated moderate precision.

Observational cohorts targeting acute hospitalization durations [15,18] were relatively less certain. While these studies reported significant trends in morbidity, especially regarding respiratory and infectious complications in the early phases, their drawbacks were established by short follow-up durations and imprecise outcome measures, with less confidence in their generalizability in the long term.

Longitudinal observational studies [16,17] were of moderate grade, based on low risk of bias and consistent findings on the predictive effect of age at injury and the necessity for longitudinal follow-up. These articles made important contributions to establishing that scoliosis and autonomic dysregulation remain risks through extended recovery, with directly relevant data and acceptably accurate estimates.

Structured interview cohort studies [21,22] were also of moderate certainty with low risk of bias and consistent evidence on long-term urologic and musculoskeletal sequelae in children with SCI. They were able to determine functional limitation and bladder and spasticity management needs with validated measures on long-term follow-up, hence more clinically useful and stronger in conclusion.

DISCUSSION

Pediatric traumatic SCI represents a distinctive clinical problem because of the complex interplay between developmental neurobiology, biomechanical susceptibility and long-term functional outcome. In contrast with SCI in adults, pediatric injury most commonly occurs during periods of critical neural development and plasticity, resulting in complex patterns of recovery, complications and adaptation. Pediatric SCI pathophysiology also varies markedly from that in adults because of spinal column compliance, immaturity of myelination and heterogeneity of expression levels of neurotrophic factors, all of which affect both the initial injury and the ensuing cascade of injury [23]. This inflammation-ischemia-apoptosis-glial scarring cascade is pivotal to the long-term outcome and novel evidence suggests that interventions aimed against secondary injury mechanisms may offer a window of therapeutic opportunity [24,25].

Majority of the included studies [14,16,19-20,22] were consistent in advocating early, preventive and long-term approaches. Kulshrestha *et al.* [17] offered age-related orthopedic specificity, whereas Malhotra *et al.* [18], as well as González-Paesani *et al.* [15], placed greater emphasis on acute intervention, with some variation of scope and follow-up duration. Concurring despite differences in method, overall conclusion reiterated the importance of early detection, rehabilitation in its broadest sense and ongoing monitoring in maximizing pediatric SCI outcomes.

González-Paesani *et al.* [15] similarly did so in this regard, focusing on timely identification of respiratory complications in the context of acute hospitalization. Although long-term follow-up information was not available in this research, the results were directionally in line with Novoselova *et al.* [20] and Malhotra *et al.* [18], both of which highlighted acute-phase treatment. The latter indicated that high morbidity, especially in cervical SCI, required early surgical and clinical treatment, as with the acute care considerations of González-Paesani *et al.* [15].

Hwang *et al.* [16] and Vogel *et al.* [22] further broadened the scope by highlighting the necessity of longitudinal surveillance. Their evidence provided support for correlations of injury severity, aging and complication development like UTIs, autonomic dysreflexia and respiratory dysfunction. The evidence strengthened that of Vogel *et al.* [21], which also provided evidence for musculoskeletal sequelae like spasticity and pain, further strengthening the necessity of surveillance for chronic complications. The three studies collectively showed high congruence in the evidence for long-term outcome assessment.

Conversely, Kulshrestha *et al.* [17] offered a slightly different emphasis by specifying the age at which the injury occurs-namely below 14.6 years-as a risk indicator of onset of scoliosis. Although this was consistent with the overall discussion regarding risk evaluation in the initial phase, it differed somewhat from the wide range of complications evaluated by other studies, confining its emphasis primarily to orthopedic outcomes.

Conversely, Malhotra *et al.* [18] were greatly at variance with the rest of the studies in scope and temporality since they were interested only in in-hospital adverse events like pneumonia, pressure ulcers and cardiac complications. This acute focus was in sharp contrast to the more preventive and longitudinal focus of Hwang *et al.* [16], Meng *et al.* [19] and Vogel *et al.* [22].

Arguably the most significant issue in the care of pediatric SCI is the disproportionate incidence of secondary complications like spasticity, neuropathic pain, scoliosis,

neurogenic bladder and respiratory dysfunction. Not only do they detract from quality of life but also create undue healthcare utilization and caregiver burden. Adult evidence has had considerable influence on a great deal of clinical practice, but pediatrics-specific issues like growth-related spinal deformity, endocrine disturbance through hypothalamic-pituitary axis injury and developmental delay in bladder and bowel control necessitate special solutions [26,27]. Presentation of pituitary stalk transection syndrome following traumatic injury is a very dramatic illustration of the endocrine subtleties in this population [25].

More recent developments in neuroregeneration and rehabilitation methodologies, including the use of biofunctionalized scaffolds, cellular therapy and neurostimulation methods like epidural spinal cord stimulation, have been investigated with promising preclinical results [24,26,28]. However, the translation of these methods into clinical pediatric care is complicated by issues of design, ethics and variability of the injury profile. The involvement of inflammatory mediators, however, such as cytokines and chemokines, in perinatal and early life injury is open to opportunities for the discovery of putative biomarkers and early intervention targets [29].

In addition, urinary and gastrointestinal dysfunctions-neurogenic bladder-are established as common and severe complications [30]. These dysfunctions are most likely to be worsened by improper bladder management habits, resulting in persistent infection, renal injury and negative psychosocial impact. Empirical data have established that secretomes of apoptotic mononuclear cells and neuroprotectants like deferoxamine can diminish these effects by modulating inflammatory processes and enhancing axonal integrity [28,31].

The risk of developing complications is a function of sex, the age at which the injury is sustained and access to care. Disparities in trauma care delivery and access to rehabilitation have been observed in pediatric populations, especially females and comprise delays in the provision of care or decreased post-discharge support services [32,33]. The disparities emphasize the importance of health policies and infrastructure that promote equity to enhance outcomes. On the molecular level, the regulatory processes mediated by sulfonylurea receptor protein 1 (Sur1) have emerged as a crucial factor in Central Nervous System (CNS) injury and provide additional pharmacological targets for intervention [34]. Preventive interventions should be employed in the management of complication rates. For example, silver-coated urinary catheters reduce urinary tract infection rates, a high-risk complication of Spinal Cord Injury (SCI) patients [35].

Moreover, proper anatomical and neurological classification and identification of unusual traumatic variations such as spondyloptosis without neurological deficit are needed to individualized treatment planning [36]. Simultaneous Traumatic Brain Injury (TBI) and SCI diagnoses are not rare among children and have been linked to increased neurocognitive and functional impairment [37]. Metabolic interventions, specifically ketogenic in nature, have been identified with neuroprotective benefit in preclinical central nervous system models of injury, enlarging the therapeutic window [38]. Epidemiologic studies in the low-resource environment of Tanzania have identified context-specific risk factors and system-level health issues disproportionately impacting the management of pediatric spinal cord injury [39]. Multimodal rehabilitation models with tele-exercise, music therapy and robot assistance are increasingly identified to provide promise for maximizing motor recovery as well as psychological outcomes in children with spinal cord injury [40-43].

CONCLUSION

The observed findings indicate to the fact that secondary complications of pediatric traumatic SCI were common and clinically heterogeneous and their presence and severity were a function of age at injury, injured neurological level and completeness of the lesion. Early identification, organized long-term follow-up and targeted rehabilitation interventions were essential to prevent complications. The findings highlighted the importance of standardised assessment protocols and evidence-based guidelines for pediatric patients to optimise long-term care outcomes of this patient group.

Limitations

This review was hampered by heterogeneity of study design, patient groups and outcome reporting of the studies included. Differences in assessment tools, diagnostic criteria and follow-up intervals prevented direct comparability of findings and the feasibility of meta-analytical pooling. Application of non-randomized observational data was associated with inherent risks of confounding and bias, particularly in those studies that did not adjust for injury severity or baseline function. In addition, some studies presented incomplete or inconsistent reporting of key variables such as injury completeness, time of assessment and outcome of intervention, thereby narrowing the scope of interpretation. Exclusion of articles published in languages other than English may have introduced language bias and publication bias could not be completely excluded.

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