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Comment & Opinion

Guidelines for management of pediatric acute hyperextension spinal cord injury

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ABSTRACT

Pediatric acute hyperextension spinal cord injury (SCI) named as PAHSCI by us, is a special type of thoracolumbar SCI without radiographic abnormality and highly related to back-bend in dance training, which has been increasingly reported. At present, it has become the leading cause of SCI in children, and brings a heavy social and economic burden. Both domestic and foreign academic institutions and dance education organizations lack a correct understanding of PAHSCI and relevant standards, specifications or guidelines. In order to provide standardized guidance, the expert team formulated this guideline based on the principles of science and practicability, starting from the diagnosis, differential diagnosis, etiology, admission evaluation, treatment, complications and prevention. This guideline puts forward 23 recommendations for 14 related issues.

Introduction

Spinal cord injury (SCI) is a type of highly disabling disease with temporary or permanent neurological dysfunction below the level of SCI caused by various reasons, which brings a heavy social and economic burden. SCI is more common in adults than children. Comparing to adults, children receive additional protection of ethical review in the process of clinical research,[1] so most research and guidelines of SCI focus on adults. However, compared with adult patients, children with SCIs have a longer lifespan with more complex and serious complications. It is more difficult for clinicians to properly diagnose and treat children with SCIs under the condition of limited clinical research and guidelines.

More worryingly, in recent years, a special type of thoracolumbar SCI without radiographic abnormality (SCIWORA), which is highly related to back-bend in dance training, has been increasingly reported.[2–5] Considering that it may have different pathogenesis, epidemiology and clinical manifestations from typical SCIWORA, we named this special SCIWORA as pediatric acute hyperextension spinal cord injury (PAHSCI).

There are a huge number of children in China. With the Chinese double reduction policy and Chinese parents' continuous emphasis

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on children's quality education, more and more children participate in dance training. It is foreseeable that the incidence of PAHSCI will increase steadily. However, due to the lack of understanding and unfamiliarity, PAHSCI is sometimes misdiagnosed, or even given inappropriate diagnosis and treatment. Therefore, there is an urgent need for a guideline of PAHSCI, which provides standardized guidance for the prevention, pre-hospital emergency first aid, diagnosis, treatment, complications and rehabilitation training.

Methods and evidences

A total of 483 pieces of literature were retrieved by searching and screening in the database of CNKI, Wanfang, VIP, Web of Science and PubMed before November 2021. Later, intensive reading and sorting were carried out by reading abstracts, and 51 papers were retained after the second screening. According to the need for literature evaluation and supplementary guidelines, the first draft was formed and discussed by the expert group. According to the deep discussion, the final version of the questionnaire was formed and distributed to the expert group. For the completed questionnaires, choices of each expert were counted, and the expert recommendation rate was calculated. After that, the completed questionnaires by the experts were analyzed again, then the first draft of the text was formed, and finally this guideline was formulated through the review of each expert.

Level of evidence

The Assessing Methodological Quality of Systematic Reviews was adopted to evaluate the methodological quality of systematic reviews and meta-analyses,[6] and the Cochrane risk of bias assessment tool to evaluate randomized controlled trials.[7] For observational studies, the Newcastle-Ottawa Scale was used to evaluate the methodological quality of the corresponding types of studies.[8] According to the Grading of Recommendations Assessment, the Development and Evaluation method,[9] the literature evidence level is divided into four levels, and the recommendation strength is divided into three levels, decreasing gradually from Level I to Level III.

Evidence level

Level I: Prospective randomized controlled studies, systematic reviews and meta-analyses.
Level II: Prospective non-randomized controlled studies.
Level III: Retrospective case-control study.
Level IV: Case series report.

Recommended strength level

Level I: High-quality Level I evidence studies with statistically significant differences; high-quality Level I evidence studies with narrow confidence intervals although the differences are not statistically significant; systematic reviews of Level I evidence studies (provided that these results of the included studies were homogeneous).
Level II: Level I evidence studies of lesser quality (e.g., follow-up rate < 80%, unblinded control, inappropriate randomization); Level II evidence studies; systematic reviews of Level I evidence studies with heterogeneous findings; systematic review of Level II evidence studies.
Level III: Level III or Level IV evidence studies.

Definition and characteristic of PAHSCI

Definition of PAHSCI

PAHSCI refers to the acute thoracolumbar SCI without fracture and dislocation in children after hyperextension of the spine, especially during back-bend in dance training (Fig. 1). SCIWORA was first proposed by Pang and Wilberger in 1982.[10] With the emergence and popularization of imaging techniques such as CT, MRI and other imaging equipment, it is currently believed that SCIWORA refers to the absence of evidence of fracture or malalignment on plain radiographs and CT of the spine.[11] Epidemiology shows that the incidence of SCIWORA in the cervical spine is much higher than that in the thoracic and lumbar spine, and the incidence of boys is higher than that of girls. It is usually caused by high-energy injuries such as sports injuries, car accidents and falls. This is because the spine of children is relatively flexible, the head-to-body ratio is large, the vertebral body is wedge-shaped, the articular surface is shallow and horizontal, the interspinous ligament is loose and elastic, and the neck muscle is underdeveloped. Because of the surrounding thoracic and costal joints, the thoracic spine is more stable than the cervical spine, so the rate of SCIWORA is very low. However, unlike typical SCIWORA, PAHSCI almost exclusively occurs in the thoracic and lumbar spine usually without external violence, and is closely related to back-bend in dance, of which the incidence is much higher in girls than boys.

Clinical manifestations of PAHSCI

Children with PAHSCI have no symptoms of cold, diarrhea, fever, chills, etc., no recent history of vaccination, and no other neurological diseases before the onset. PAHSCI is most seen in back-bend

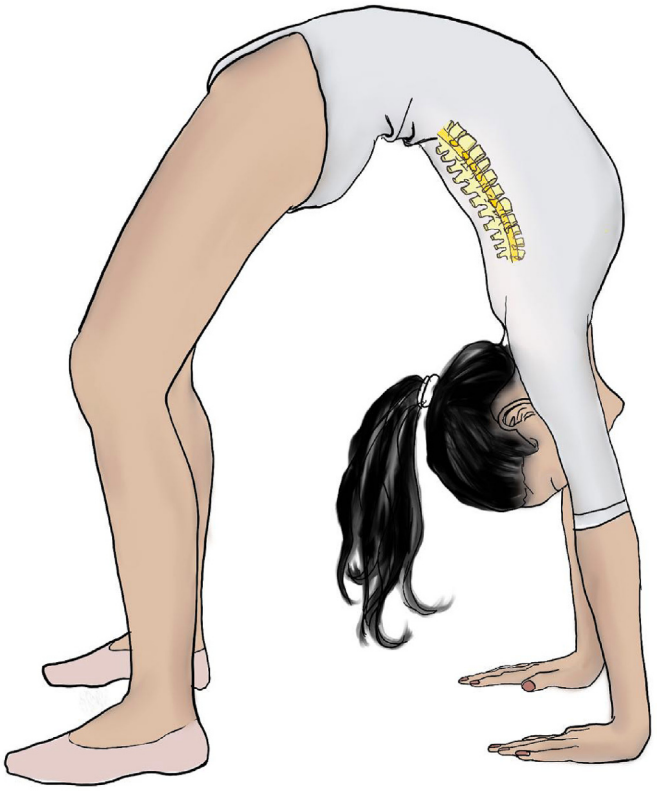

Fig. 1. Schematic diagram of back-bend during dance training.

of traditional Chinese dance training. Most children with PAHSCI experience lower limb pain and paresthesia during hyperextension of the spine, and often fall due to weakened strength or pain. Usually, the early manifestations are soreness and discomfort in the waist, low back pain, leg pain, numbness, or weakness of the lower limbs, but most children can stand and walk. After a few hours, the neurological symptoms of the patients progressively worsened and developed to typical symptoms of SCI below the injury level.[2,3,5,12,13]

The clinical sign of children with PAHSCI is mostly paraplegia, and most of them show complete SCI after admission. The nerve injury plane is distributed from T_4 to T_{12}, of which the most common lesions are above and below T_{10}. Sensory and motor loss occurs below the injury level, as well as urinary and bowel dysfunction. Pathological signs were negative. Patients with complete SCI all showed flaccid paralysis, and spastic paralysis may occur in the later stage of incomplete SCI.[2,3,5,12,13]

Fractures, dislocations or obvious developmental abnormalities are usually not found in spinal X-ray and CT examinations of children with PAHSCI. Diffuse edema hyperintense shadows in the middle/lower thoracic spinal cord to the conus medullaris can be seen on spinal MRI examination in the acute phase. In the subacute phase of complete SCI, the length of intramedullary lesions will increase to the cranial and caudal sides of the spinal cord, but the neurological function of most children will not deteriorate further. The level of nerve injury does not completely match the results of MRI examination in the acute phase.[2,3,5,13,14] In a small number of patients with mild symptoms, an MRI examination of the spinal cord may appear normal.[15,16] MRI can be dynamically reviewed to evaluate the condition.[13,17,18]

Epidemiology of PAHSCI

Since PAHSCI unlike typical SCIWORA has only received extensive attention in recent years, the reliable epidemiology is still lacking. According to the existing literature reports, there are more than 200 cases of children with PAHSCI caused by back-bend in dance, and the vast majority is girls, mainly aged 3—10 years. From 1992 to 2002, children with SCI caused by back-bend in dance accounted for only 4.0% of all children with SCI, while from 2015 to 2019 it increased to 33.9%, accounting for 64.1% of SCIWORA. It has become the leading cause of SCI in children.[5,19]

Pathogenesis of PAHSCI

The pathogenesis of PAHSCI in children is still unclear and controversial at home and abroad. Due to the obvious latency and progressive exacerbation characteristics of PAHSCI, most researchers believe that PAHSCI is caused by spinal cord ischemia.[2,12,20,21] It is speculated that the possible pathogenesis is as follows: (1) Spinal cord venous disease: When the spinal cord is hyperextended, local small venous injury occurred due to retraction of the conus medullaris-cauda equina junction, transient dislocation of apical vertebra, and compression of anterior longitudinal ligament and posterior longitudinal ligament. After local small venous injury, spinal cord venous reflux is obstructed, resulting in spinal cord venous hypertension. In turn, it leads to changes in the spinal arteriovenous pressure gradient, and leads to insufficient blood supply of the spinal cord, ischemia edema, and the emergence of spinal cord compartment syndrome or intraspinal hypertension, which eventually results in spinal venous infarction; (2) Spinal cord arterial disease: When the spinal cord is hyperextended, damage for the artery nourishing the spinal cord leads to insufficient blood supply to the spinal cord; (3) Spinal cord vascular thrombosis: Spinal cord vascular embolism leads to spinal cord infarction, such as venous thromboembolism, spinal vascular fibrocartilaginous embolism, etc.; (4) Longitudinal traction injury of the spinal cord: Since the longitudinal extension of the spinal cord is much less than the longitudinal extension of the spinal canal, when the spine is hyperextended, it results in longitudinal hyperextension of the spinal cord; (5) Lateral spinal cord impingement injury: When the spine is hyperextended, the vertebral body, intervertebral disc and ligament temporarily protrude into the spinal canal, resulting in spinal cord impingement injury.[2,3,5,12–14,20–24] However, the currently speculated pathogenesis lacks strong evidence support and needs to be further explored.

Recommendations

How to prevent PAHSCI in children?

Recommendation 1a: It is not recommended for all children to participate thoracic spinal hyperextension exercises, such as back-bend in dance, especially for children under the age of 10.

Recommendation1b: If thoracic spinal hyperextension exercises are really required, physical examination should be firstly carried out by a specialist to evaluate physical condition, and the performance should be under the close guidance of professional institutions and professional teachers.

How to perform pre-hospital first aid for children with PAHSCI?

Recommendation 2: In the process of spinal hyperextension training, such as dance back-bend, if neurological symptoms occur, it should be immobilized immediately and transferred to a specialized hospital for treatment. PAHSCI usually has mild neurological symptoms in the early stage of onset. Most of the children fail to go to the hospital for treatment in time, and the dance training and daily life are still continued as normal. Therefore, it may not only miss the best treatment time, but also aggravate the existing SCI and even cause secondary losses. For SCI, time is spine,[25–27] and earlier is better.[28] The earlier intervention of SCI, the better the curative effect of SCI patients. And the irreversible damage caused by ischemia may occur after 36 h.[29]

How to perform physical examination on children with PAHSCI?

Recommendation 3a: After admission, neurological function tests should be immediately performed according to the latest version of the American Spinal Injury Association (ASIA) standards,[30] and the neurological dysfunction of SCI should be graded using the ASIA impairment scale (Level III).

Recommendation 3b: All children should have a routine digital rectal examination for anal sensation and anal sphincter function (Level III).

As an important part of the ASIA standard, digital rectal examination is recommended because it is highly prognostic and differs from typical SCIs. Children with incomplete SCI usually recover to a certain degree of walking ability or even return to normal. However, it is important to note that children under the age of 5 often do not cooperate well with the physical examination due to insufficient cognitive development during the neurologiccal examination.[31]

How to conduct auxiliary examinations for children with PAHSCI?

Recommendation 4a: Spinal X-ray and CT should be used as routine examinations for children with PAHSCI (Level III).

Recommendation 4b: Spinal MRI and magnetic resonance angiography should be used as routine examinations for children with PAHSCI (Level III).

Recommendation 4c: Spinal cord angiography can be used as a diagnosis option in qualified hospitals (Level III).

Recommendation 4d: Quantitative MRI, such as diffusion tensor imaging can be used as a diagnosis option in qualified hospitals.

Recommendation 4e: Cerebrospinal fluid examination can be considered as a diagnosis option when it is difficult to differentiate from acute myelitis or other types of SCIs (Level III).

Spinal X-rays and CT can help rule out a spinal fracture or dislocation, and MRI can help determine the extent of SCI. At present, most experts believe that this type of injury is ischemic injury of the spinal cord,[2,12,13,20,21] which is caused by congenital or acquired lesions of the spinal cord blood vessels. Therefore, magnetic resonance angiography is recommended as a routine examination to check spinal cord blood vessels, when considering PAHSCI may provide more accurate diagnosis (Level III).[32–34]

Should methylprednisolone be used in children with PAHSCI?

Recommendation 5: Methylprednisolone sodium succinate can be used as a treatment option within 8 h of PAHSCI (Level III).

Clinical research for SCI has been slow and treatment options are very limited.[35] Studies have shown that drug intervention can reduce secondary injury and inflammation, as well as promote the recovery of neurological function to a certain extent.[36–38] At the end of last century, 3 studies of National Acute Spinal Cord Injury Study on methylprednisolone sodium succinate in traumatic SCI made methylprednisolone sodium succinate widely used in adult traumatic SCI, which preliminarily established the method of administration of methylprednisolone in adults. However, so far, there is insufficient evidence to support it as a standard treatment regimen, and further research is needed.[39] Moreover, the US Food and Drug administration has not approved high-dose methylprednisolone sodium succinate therapy for SCI.[40] Therefore, high-dose methylprednisolone pulse therapy is currently only used as a treatment option or not recommended for adult with SCI, rather than as a routine treatment regimen.[41]

At present, there are few studies on methylprednisolone in children with traumatic SCI, especially in children under the age of 13.[42] There is still insufficient evidence to determine whether methylprednisolone is used in the treatment of PAHSCI, and further research is needed. Considering that children with SCI may have better potential for neurological recovery than adults,[43] we considered high-dose methylprednisolone pulse as an experimental treatment option for PAHSCI, which needs to be used according to the experience. At present, there is no reliable high-dose methylprednisolone pulse therapy for children with SCI, and most doctors adopt this method with reference to methylprednisolone therapy for adults with SCI.[42]

Should gangliosides be used in children with PAHSCI?

Recommendation 6: Gangliosides are not recommended as routine treatment without demonstrated clinical benefit (Level III). No further studies have confirmed that SCI patients can benefit from it. Therefore, ganglioside is not recommended as routine management of children with PAHSCI.

How to control blood pressure for PAHSCI?

Recommendation 7: In order to enhance the perfusion of the spinal cord, appropriate vasoactive drugs can be used to maintain the average mean arterial pressure in children above 85 mmHg within 7 days.[17,44,45] Current studies suggest that PAHSCI may be mainly caused by ischemia of spinal cord, and maintaining mean arterial pressure above 85 mmHg may improve spinal cord perfusion.

Should surgery be performed on children with PAHSCI?

Recommendation 8: Conservative treatment is the main treatment for children with PAHSCI. However, if there is a hematoma in the spinal canal or spinal cord of a child with PAHSCI, continued compression of the spinal cord results in high intramedullary pressure, or if the range of spinal cord edema increases rapidly and the symptoms of nerve injury continue to aggravate,[17,46,47] early and adequate decompression surgery may be considered as an option treatment.

How to immobilize the brace for children with PAHSCI?

Recommendation 9: It is recommended to stay in bed for 6 weeks, and then to continue to protect with external fixation with bracing for at least 6 weeks and perform rehabilitation treatment as soon as possible under the protection.[15,16,37,48]

Is it necessary to prevent deep vein thrombosis with chemical medicines or surgery?

Recommendation 10a: The use of low molecular weight heparin to prevent deep vein thrombosis is not recommended as a routine treatment.[49]

Recommendation 10b: Inferior vena cava filters are not recommended as routine preventive measures.[49] Deep vein thrombosis is a rare complication in children with SCI, and the risk of developing deep vein thrombosis in children below the age of 12 years is very low, so chemoprophylaxis or surgery is not routinely recommended unless other significant risk factors are present.[50]

How to prevent scoliosis in children with PAHSCI?

Recommendation 11: We recommend that spine plain radiographs should be conducted every 6 months to evaluate scoliosis (Level III). Scoliosis is the most common complication after SCI in children. It is reported that 96% of children with SCI will have different degrees of scoliosis in long-term follow-up,[51] which often leads to severe deformities and affects the cardiopulmonary function and physical development of children.[5,51–53] Therefore, regular examination should be carried out. Once more serious scoliosis is found, the brace should be worn to prevent scoliosis from getting worse.

How to prevent neurogenic osteoporosis in children with PAHSC?

Recommendation 12a: We recommend that calcium supplementation and vitamin D are important supplementation for children with PAHSCI (Level III).

Recommendation 12b: We recommend that bone mineral density testing, such as dual-energy X-ray absorptiometry scans, should be conducted every 6 months to evaluate osteoporosis, and additional attention should be paid to assess whether children have spontaneous fractures (Level III).

Neurogenic osteoporosis refers to the loss of bone mass and the destruction of bone microstructure due to lack of mechanical stimulation, denervation of bone tissue and hormones changes after SCI.[55,54]

At present, there is no specific diagnostic standard for neurogenic osteoporosis. For the diagnosis of osteoporosis in children, we follow the recommendations of the International Society for Clinical Densitometry on the diagnosis of osteoporosis in children: the diagnosis required the presence of both a clinically significant fracture history ($\geq$ 2 long bone fractures by age 10 years, or $\geq$ 3 long bone fractures by 19 years), and a low age- and gender-matched bone mineral density Z-score of ≤ -2.0 (with appropriate

corrections for bone size). Vertebral compression fractures in children with low-trauma can be diagnosed as pediatric osteoporosis even without bone mineral density.[57,56] At present, there is no effective drug treatment and preventive measures for neurogenic osteoporosis after SCI.[58] Active or passive rehabilitation training, combined with physical therapy such as functional electrical stimulation, pulsed electromagnetic fields, or exoskeleton robots may play a certain role in the prevention and treatment of PAHSCI.[59,60] If necessary, careful selection of appropriate bone resorption inhibitors or bone formation promoters can prevent the occurrence of osteoporosis.

How to prevent urinary complications in children with PAHSC?

Recommendation 13a: Early indwelling catheterization is recommended to protect bladder and renal function in children with PAHSCI. After partial recovery of bladder function, intermittent catheterization and bladder function exercise are recommended (Level III).

Recommendation 13b: Nerve transposition can be used as a treatment option, if it meets the indication (Level III).

How to prevent bedsores in children with PAHSCI

Recommendation 14: We recommend that patients with PAHSCI should turn over regularly. Care should be taken to avoid the stimulation of moisture, friction and excrement of patients, prevent skin damage due to prolonged pressure or friction,[61] ensure a healthy and nutritious diet, and maintain local blood circulation.

Care should be taken to avoid the stimulation of moisture, friction and excrement of patients, prevent skin damage due to prolonged pressure or friction,[61] ensure diet and nutrition, and maintain local blood circulation.

Although children with SCI are less likely to develop bedsores than adults,[62] bedsores should still be of high concern as a serious complication of SCI.

Statement

This guideline only includes PAHSCI which refers to acute thoracolumbar SCIWORA after repeated or persistent hyperextension of the spine in children, excluding trauma-related thoracolumbar fracture-dislocation or non-fracture-dislocation SCI, children with non-fracture-dislocation cervical SCI, myelopathy in adult surfers, myelitis and spinal cord injuries of other causes. The purpose of this article is to provide standardized guidance for the diagnosis, evaluation, treatment, complications and prevention of PAHSCI. The recommendations are formed according to the principles of evidence-based medicine by consulting the existing literature and summarizing the expert opinions through many expert seminars. However, with the in-depth study of PAHSCI and more high-quality clinical research evidence, the views of the current guidelines may be updated. This guideline is not a necessary standard for the diagnosis and treatment of PAHSCI, which is only used as academic guidance and suggestion, not as a legal basis. In actual clinical work, due to individual differences in patient conditions and complex and changeable clinical conditions, this guideline should be applied according to specific situation.

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Ethical statement

Not applicable.

Declaration of competing interest

All authors declare that there is no conflict of interest.

Author contributions

Lian Zeng, Yu-Long Wang, Xian-Tao Shen, Zhi-Cheng Zhang, GuiXiong Huang, Jamal Alshorman, Tracy Boakye Serebour: guide writing; Expert group: data collection, guide discussion and revision.

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References

1. Roth-Cline MD, Gerson J, Bright P, et al. Ethical considerations in conducting pediatric research. In: Seyberth HW, Rane A, Schwab M, eds. *Pediatric Clinical Pharmacology*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2011:219–244.
2. Wang YL, Zhu FZ, Zeng L, et al. Surfer myelopathy in children: a case series study. *World Neurosurg*. 2021;148:227–241. https://doi.org/10.1016/j.wneu.2020.12.135.
3. Ren J, Zeng G, Ma YJ, et al. Pediatric thoracic SCIWORA after back bend during dance practice: a retrospective case series and analysis of trauma mechanisms. *Childs Nerv Syst*. 2017;33:1191–1198. https://doi.org/10.1007/s00381-017-3407-0.
4. Zou ZW, Teng A, Huang LY, et al. Pediatric spinal cord injury without radiographic abnormality: the Beijing experience. *Spine*. 2021;46. https://doi.org/10.1097/BRS.0000000000004030.
5. Liu GL, Zhou HJ, Li JJ, et al. Clinical manifestations and MRI features of pediatric spinal cord injury after back bend. *Chin J Rehabil Theory Pract*. 2021;27:456–465. https://doi.org/10.3969/j.issn.1006-9771.2021.04.011.
6. Higgins JPT, Altman DG, Gøtzsche PC, et al. The Cochrane Collaboration's tool for assessing risk of bias in randomised trials. *BMJ*. 2011;343. https://doi.org/10.1136/bmj.d5928.
7. Stang A. Critical evaluation of the Newcastle-Ottawa scale for the assessment of the quality of nonrandomized studies in meta-analyses. *Eur J Epidemiol*. 2010;25:603–605. https://doi.org/10.1007/s10654-010-9491-z.
8. Atkins D, Eccles M, Flottorp S, et al. Systems for grading the quality of evidence and the strength of recommendations I: critical appraisal of existing approaches the GRADE Working Group. *BMC Health Serv Res*. 2004;4:38. https://doi.org/10.1186/1472-6963-4-38.
9. Zeng L, Brignardello-Petersen R, Guyatt G. When applying GRADE, how do we decide the target of certainty of evidence rating? *Evid Base Ment Health*. 2021;24:121–123. https://doi.org/10.1136/ebmental-2020-300170.
10. Pang D, Wilberger Jr JE. Spinal cord injury without radiographic abnormalities in children. *J Neurosurg*. 1982;57:114–129. https://doi.org/10.3171/jns.1982.57.1.0114.
11. Atesok K, Tanaka N, O'Brien A, et al. Posttraumatic spinal cord injury without radiographic abnormality. *Adv Orthop*. 2018;2018, 7060654. https://doi.org/10.1155/2018/7060654.
12. Tong AN, Zhang JW, Zhou HJ, et al. Ischemic damage may play an important role in spinal cord injury during dancing. *Spinal Cord*. 2020;58:1310–1316. https://doi.org/10.1038/s41393-020-0503-x.
13. Wang YL, Zeng L, Zhu FZ, et al. Acute hyperextension myelopathy in children: radiographic predictors of clinical improvement. *Spinal Cord*. 2022;60:1–6. https://doi.org/10.1038/s41393-021-00739-w.
14. Nakamoto BK, Siu AM, Hashiba KA, et al. Surfer's myelopathy: a radiologic study of 23 cases. *AJNR Am J Neuroradiol*. 2013;34:2393–2398. https://doi.org/10.3174/ajnr.A3599.
15. Zhang L, Zhai X, Li LS, et al. Clinical characteristics, diagnosis and treatment of pediatric spinal cord injury without bone fracture or dislocation. *Chin J Neurosurg*. 2020;36:908–912. https://doi.org/10.3760/cma.j.cn112050-20200405-00206.
16. Pang D. Spinal cord injury without radiographic abnormality in children, 2 decades later. *Neurosurgery*. 2004;55:1325–1343. https://doi.org/10.1227/01.neu.0000143030.85589.e6.
17. Guo XD, Feng YP, Sun TS, et al. Clinical guidelines for neurorestorative therapies in spinal cord injury (2021 China version). *J Neurorestoratol*. 2021;9:31–49. https://doi.org/10.26599/JNR.2021.9040003.

18. Boese CK, Oppermann J, Siewe J, et al. Spinal cord injury without radiologic abnormality in children: a systematic review and meta-analysis. *J Trauma Acute Care Surg*. 2015;78:874–882. https://doi.org/10.1097/TA.0000000000000579.
19. Liu GL, Zhou HJ, Li JJ, et al. Etiological features of pediatric spinal cord injury. *Chin J Rehabil Theory Pract*. 2020;26:373–376. https://doi.org/10.3969/j.issn.1006-9771.2020.04.001.
20. Alva-Díaz C, Rodriguez-López E, López-Saavedra A, et al. Is Surfer's myelopathy an acute hyperextension-induced myelopathy? A systematic synthesis of case studies and proposed diagnostic criteria. *J Neurol*. 2021;269:1–10. https://doi.org/10.1007/s00415-021-10775-4.
21. Gandhi J, Lee MY, Joshi G, et al. Surfer's myelopathy: a review of etiology, pathogenesis, evaluation, and management. *J Spinal Cord Med*. 2021;44:2–7. https://doi.org/10.1080/10790268.2019.1577057.
22. Chang CWJ, Donovan DJ, Liem LK, et al. Surfers' myelopathy: a case series of 19 novice surfers with nontraumatic myelopathy. *Neurology*. 2012;79:2171–2176. https://doi.org/10.1212/wnl.0b013e31827595cd.
23. Freedman BA, Malone DG, Rasmussen PA, et al. Surfer's myelopathy: a rare form of spinal cord infarction in novice surfers: a systematic review. *Neurosurgery*. 2016;78:602–611. https://doi.org/10.1227/NEU.0000000000001089.
24. Albuja AC, Qaiser S, Lightner DD, et al. Surfer's myelopathy without surfing: a report of two pediatric patients. *Spinal Cord Ser Cases*. 2017;3, 17008. https://doi.org/10.1038/scsandc.2017.8.
25. Ahuja CS, Badhiwala JH, Fehlings MG. "Time is spine": the importance of early intervention for traumatic spinal cord injury. *Spinal Cord*. 2020;58:1037–1039. https://doi.org/10.1038/s41393-020-0477-8.
26. Ramakonar H, Fehlings MG. 'Time is Spine': new evidence supports decompression within 24 h for acute spinal cord injury. *Spinal Cord*. 2021;59:933–934. https://doi.org/10.1038/s41393-021-00654-0.
27. Badhiwala JH, Ahuja CS, Fehlings MG. Time is spine: a review of translational advances in spinal cord injury: JNSPG 75th Anniversary Invited Review Article. *J Neurosurg Spine*. 2019;30:1–18. https://doi.org/10.3171/2018.9.SPINE18682.
28. Maas AIR, Peul W, Thomé C. Surgical decompression in acute spinal cord injury: earlier is better. *Lancet Neurol*. 2021;20:84–86. https://doi.org/10.1016/S1474-4422(20)30478-6.
29. Badhiwala JH, Wilson JR, Witiw CD, et al. The influence of timing of surgical decompression for acute spinal cord injury: a pooled analysis of individual patient data. *Lancet Neurol*. 2021;20:117–126. https://doi.org/10.1016/S1474-4422(20)30406-3.
30. ASIA, ISCoS International Standards Committee. The 2019 revision of the international standards for neurological classification of spinal cord injury (ISNCSCI)—what's new? *Spinal Cord*. 2019;57:815–817. https://doi.org/10.1038/s41393-019-0350-9.
31. Chafetz RS, Gaughan JP, Vogel LC, et al. The international standards for neurological classification of spinal cord injury: intra-rater agreement of total motor and sensory scores in the pediatric population. *J Spinal Cord Med*. 2009;32:157–161. https://doi.org/10.1080/10790268.2009.11760767.
32. Freund P, Seif M, Weiskopf N, et al. MRI in traumatic spinal cord injury: from clinical assessment to neuroimaging biomarkers. *Lancet Neurol*. 2019;18:1123–1135.
33. Zhu FZ, Liu Y, Zeng L, et al. Evaluating the severity and prognosis of acute traumatic cervical spinal cord injury: a novel classification using diffusion tensor imaging and diffusion tensor tractography. *Spine*. 2021;46:687–694. https://doi.org/10.1097/BRS.0000000000003923.
34. Zhu FZ, Zeng L, Gui S, et al. The role of diffusion tensor imaging and diffusion tensor tractography in the assessment of acute traumatic thoracolumbar spinal cord injury. *World Neurosurg*. 2021;150:23–30. https://doi.org/10.1016/j.wneu.2021.01.146.
35. Caruso MC, Daugherty MC, Moody SM, et al. Lessons learned from administration of high-dose methylprednisolone sodium succinate for acute pediatric spinal cord injuries. *J Neurosurg Pediatr*. 2017;20:567–574. https://doi.org/10.3171/2017.7.PEDS1756.
36. Liu MG, Chen Q, Lai BF, et al. Diagnosis and treatment of spinal cord injury without fracture and dislocation in children. *J Clin Neuro Surg*. 2019;16:513–517. https://doi.org/10.3969/j.issn.1672-7770.2019.06.011.
37. Rozzelle CJ, Aarabi B, Dhall SS, et al. Spinal cord injury without radiographic abnormality (SCIWORA). *Neurosurgery*. 2013;72:227–233. https://doi.org/10.1227/NEU.0b013e3182770ebc.
38. Hurlbert RJ, Hadley MN, Walters BC, et al. Pharmacological therapy for acute spinal cord injury. *Neurosurgery*. 2015;76:71–83. https://doi.org/10.1227/01.neu.0000462080.04196.f7.
39. Canseco JA, Karamian BA, Bowles DR, et al. Updated review: the steroid controversy for management of spinal cord injury. *World Neurosurg*. 2021;150:1–8. https://doi.org/10.1016/j.wneu.2021.02.116.
40. Walters BC, Hadley MN, Hurlbert RJ, et al. Guidelines for the management of acute cervical spine and spinal cord injuries: 2013 update. *Neurosurgery*. 2013;60:82–91. https://doi.org/10.1227/01.neu.0000430319.32247.7f.
41. Fehlings MG, Wilson JR, Tetreault LA, et al. A clinical practice guideline for the management of patients with acute spinal cord injury: recommendations on the use of methylprednisolone sodium succinate. *Global Spine J*. 2017;7:203–211. https://doi.org/10.1177/2192568217703085.
42. Pettiford JN, Bikhchandani J, Ostlie DJ, et al. A review: the role of high dose methylprednisolone in spinal cord trauma in children. *Pediatr Surg Int*. 2012;28:287–294. https://doi.org/10.1007/s00383-011-3012-3.
43. Parent S, Mac-Thiong JM, Roy-Beaudry M, et al. Spinal cord injury in the pediatric population: a systematic review of the literature. *J Neurotrauma*. 2011;28:1515–1524. https://doi.org/10.1089/neu.2009.1153.
44. Squair JW, Bélanger LM, Tsang A, et al. Spinal cord perfusion pressure predicts neurologic recovery in acute spinal cord injury. *Neurology*. 2017;89:1660–1667. https://doi.org/10.1212/WNL.0000000000004519.
45. Saadeh YS, Smith BW, Joseph JR, et al. The impact of blood pressure management after spinal cord injury: a systematic review of the literature. *Neurosurg Focus*. 2017;43:20. https://doi.org/10.3171/2017.8.FOCUS17428.
46. Zhu FZ, Yao S, Ren ZW, et al. Early durotomy with duroplasty for severe adult spinal cord injury without radiographic abnormality: a novel concept and method of surgical decompression. *Eur Spine J*. 2019;28:2275–2282. https://doi.org/10.1007/s00586-019-06091-1.
47. Qu YZ, Guo XD. Durotomy and dural grafting to treat lower cervical spine injuries with extensive spinal cord edema. *Neural Regen Res*. 2015;10:1969–1970. https://doi.org/CNKI:SUN:SJZY.0.2015-12-038.
48. Srinivasan V, Jea A. Pediatric thoracolumbar spine trauma. *Neurosurg Clin*. 2017;28:103–114. https://doi.org/10.1016/j.nec.2016.07.003.
49. Powell A, Davidson L. Pediatric spinal cord injury: a review by organ system. *Phys Med Rehabil Clin*. 2015;26:109–132. https://doi.org/10.1016/j.pmr.2014.09.002.
50. Jones T, Ugalde V, Franks P, et al. Venous thromboembolism after spinal cord injury: incidence, time course, and associated risk factors in 16,240 adults and children. *Arch Phys Med Rehabil*. 2005;86:2240–2247. https://doi.org/10.1016/j.apmr.2005.07.286.
51. Schottler J, Vogel LC, Sturm P. Spinal cord injuries in young children: a review of children injured at 5 years of age and younger. *Dev Med Child Neurol*. 2012;54:1138–1143. https://doi.org/10.1111/j.1469-8749.2012.04411.x.
52. Kulshrestha R, Kuiper JH, Masri WEl, et al. Scoliosis in paediatric onset spinal cord injuries. *Spinal Cord*. 2020;58:711–715. https://doi.org/10.1038/s41393-020-0418-6.
53. Mulcahey MJ, Gaughan JP, Betz RR, et al. Neuromuscular scoliosis in children with spinal cord injury. *Top Spinal Cord Inj Rehabil*. 2013;19:96–103. https://doi.org/10.1310/sci1902-96.
54. Shams R, Drasites KP, Zaman V, et al. The pathophysiology of osteoporosis after spinal cord injury. *Int J Mol Sci*. 2021;22:3057. https://doi.org/10.3390/ijms22063057.
55. Frotzler A, Krebs J, Göhring A, et al. Osteoporosis in the lower extremities in chronic spinal cord injury. *Spinal Cord*. 2020;58:441–448. https://doi.org/10.1038/s41393-019-0383-0.
56. Bishop N, Arundel P, Clark E, et al. Fracture prediction and the definition of osteoporosis in children and adolescents: the ISCD 2013 Pediatric Official Positions. *J Clin Densitom*. 2014;17:275–280. https://doi.org/10.1016/j.jocd.2014.01.004.
57. Ward LM, Weber DR, Munns CF, et al. A contemporary view of the definition and diagnosis of osteoporosis in children and adolescents. *J Clin Endocrinol Metab*. 2020;105:2088–2097. https://doi.org/10.1210/clinem/dgz294.
58. Soleyman-Jahi S, Yousefian A, Maheronnaghsh R, et al. Evidence-based prevention and treatment of osteoporosis after spinal cord injury: a systematic review. *Eur Spine J*. 2018;27:1798–1814. https://doi.org/10.1007/s00586-017-5114-7.
59. Huang R, Zeng L, Cheng H, et al. Editorial: neural interface for cognitive human-robot interaction and collaboration. *Front Neurosci*. 2022;16, 830877. https://doi.org/10.3389/fnins.2022.830877.
60. Duan RM, Qu MJ, Yuan YS, et al. Clinical benefit of rehabilitation training in spinal cord injury: a systematic review and meta-analysis. *Spine*. 2021;46:398–410. https://doi.org/10.1097/BRS.0000000000003789.
61. Kottner J, Cuddigan J, Carville K, et al. Prevention and treatment of pressure ulcers/injuries: the protocol for the second update of the international Clinical Practice Guideline 2019. *J Tissue Viability*. 2019;28:51–58. https://doi.org/10.1016/j.jtv.2019.01.001.
62. Richard-Denis A, Thompson C, Bourassa-Moreau É, et al. Does the acute care spinal cord injury setting predict the occurrence of pressure ulcers at arrival to intensive rehabilitation centers? *Am J Phys Med Rehabil*. 2016;95:300–308. https://doi.org/10.1097/PHM.0000000000000381.