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Machine learning analysis of cervical balance in early-onset scoliosis post-growing rod surgery: a case-control study

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We aimed to analyze the cervical sagittal alignment change following the growing rod treatment in early-onset scoliosis (EOS) and identify the risk factors of sagittal cervical imbalance after growing-rod surgery of machine learning. EOS patients from our centre between 2007 and 2019 were retrospectively reviewed. Radiographic parameters include the cervical lordosis (CL), T1 slope, C2-C7 sagittal vertical axis (C2-7 SVA), primary curve Cobb angle, thoracic kyphosis (TK), C7-S1 sagittal vertical axis (C7-S1 SVA) and proximal junctional angle (PJA) were evaluated preoperatively, postoperatively and at the final follow-up. The parameters were analyzed using a t-test and χ2 test. The machine learning methodology of a sparse additive machine (SAM) was applied to identify the risk factors that caused the cervical imbalance. 138 patients were enrolled in this study (96 male and 42 female). The mean thoracic curve Cobb angle was $67.00 \pm 22.74°$. The mean age at the first operation was 8.5 ± 2.6yrs. The mean follow-up was 38.48 ± 10.87 months. CL, T1 slope, and C2-7 SVA increased significantly in the final follow-up compared with the pre-operative data. ($P < 0.05$). The CL and T1 slope increased more significantly in the group of patients who had proximal junctional kyphosis (PJK) compared with the patients without PJK ($P < 0.05$). The location of the upper instrumented vertebrae (UIV) and single/dual growing rod had no significant influence on the sagittal cervical parameters ($P > 0.05$). According to the SAM analysis of machine learning algorithms, Postoperative PJK, more improvement of kyphosis, and T1 slope angle were identified as the risk factors of cervical sagittal imbalance during the treatment of growing rod surgery. The growing rod surgery in EOS significantly affected the cervical sagittal alignment. Postoperative PJK and more improvement of kyphosis and T1 slope angle would lead to a higher incidence of cervical sagittal imbalance.

Keywords Cervical alignment, Early-Onset Scoliosis, Growing rod, Proximal junctional kyphosis, Machine learning algorithm

Early-onset scoliosis (EOS) is characterized by the onset of spinal deformity before the age of 10 years. Based on etiological classification, EOS can be delineated into idiopathic, congenital, neuromuscular, and syndromic subtypes[1]. Spinal growth velocity peaks at the age of five, while pulmonary development extends until approximately eight years of age. Consequently, severe spinal deformities in EOS patients can impede alveolar growth[2]. Affected individuals with EOS are at risk for compromised pulmonary function and, due to the associated cosmetic deformities and postural abnormalities, EOS imposes substantial psychological and economic burdens on both the affected children and their families[3].

In cases where conservative management of EOS is ineffective, growing rod surgery emerges as the principal therapeutic intervention for patients with progressive EOS. This surgical approach effectively mitigates the progression of spinal deformities while optimizing spinal and pulmonary growth and development. Empirical

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evidence supports the efficacy of growing rod surgery in correcting scoliosis and kyphosis, as well as its positive impact on pulmonary function[4]. Nevertheless, the treatment of EOS is fraught with complexity, and the potential for complications post-growing rod surgery, such as proximal junctional kyphosis (PJK), spontaneous fusion, screw loosening, incisional infection, rod breakage, screw breakage, and hook disengagement[5], presents a formidable challenge to spinal surgeons[6].

Current research examining the correlation between spinal alignment and health-related quality-of-life (HRQoL) predominantly centres on thoracolumbar and lumbosacral regions, with comparatively less focus on cervical sagittal alignment[7]. Despite growing awareness among spinal surgeons regarding the severity of complications following growing rod surgery, the alteration in overall spinal alignment and the incidence of postoperative PJK being topics of significant interest, the changes in cervical sagittal alignment following growing rod surgery have been largely overlooked[8]. To date, there has been a paucity of research on the impact of growing rod surgery on the cervical sagittal sequence in EOS patients and the associated risk factors for cervical sagittal imbalance. Our retrospective analysis of 138 EOS patients aims to investigate the effects of growing rod surgery on cervical sagittal parameters in EOS patients, to elucidate the influence of growing rod surgery on the cervical sagittal sequence in EOS, and to develop and assess a predictive model using machine learning to forecast the risk of cervical sagittal imbalance following growing rod surgery in EOS patients.

Methods
Our institutional review board approved this study, and informed consent was waived because of the retrospective study design, which was approved by the appropriate ethics review board (No.2017-KE-67). All experimental conditions conformed to the Declaration of Helsinki.

Patient selection
A retrospective consecutive case review was performed to identify patients with EOS who underwent growing-rod surgery between January 2007 and December 2019 at a single institution.

The main inclusion criteria were: 1)Patients with early-onset scoliosis (EOS), defined as onset before age 10. 2)Scoliosis types: idiopathic, congenital, neuromuscular, or syndromic. 3)Primary curve location: thoracic or thoracolumbar. 4)Primary curve Cobb angle on full-length AP radiographs > 45°. 5)Underwent initial growth rod insertion. 6)Received ≥ 2 growth rod adjustments with ≥ 24 months follow-up. 7)Complete demographic, clinical, and radiographic data pre- and postoperatively and at follow-ups. 8)The EOS patient exhibits normal upper and lower limb mobility, with no neurological symptoms present.

The exclusion criteria were: (1) Significant congenital cardiopulmonary malformations. (2) Risser sign > I. (3) Primary curve Cobb angle < 45°, not requiring surgery. 4)Scoliosis onset after age 10. 5)< 3 Growth rod adjustments or < 24 months follow-up. 6)Prior spinal surgery before growth rod insertion. 7) Lost to follow-up or complications. 8)The patient's primary curve is a lumbar curve.

Surgical technique
A single or dual growing rod and instrumented levels were determined based on the curve type and magnitude, coronal and sagittal alignment, and aetiology. Dual rod surgery was performed in patients with trunk imbalance and single rod surgery in patients with good trunk balance or skinny children. Stable vertebrae were selected as the lower instrumented vertebrae (LIV), and vertebrae cranial to the upper thoracic curve were selected as the upper instrumented vertebrae (UIV). The proximal fixation type included hooks, pedicle screws, or a hybrid. Paravertebral muscles were dissected to expose the cranial and distal bony structures for implantation. The rods were generally bent 30–40 degrees, which is consistent with the physiological kyphotic curvature. Rods were fixed with screws or hooks, placed intramuscularly, and connected by a connector. Proper distraction was performed after the rods were implanted. A bone graft was implanted at the cranial and distal foundations. Cervicothoracic braces were used in all cases after every surgery. Growing-rod lengthening surgery was performed every 12 months with 1–3 cm distractions according to the specific conditions of patients until the final correction.

### Demographic data and surgical information
Clinical, demographic data. Surgical information was analyzed, including single or dual growing-rod surgery, instrumented segments, fixation type (pedicle screw or hook or hybrid), and the number of lengthening surgeries. The institutional review board approved this study of our institution, and the privacy rights of included patients are always observed.

Radiographic evaluation
Radiographs (Fig. 1). PACS (Picture Archiving & Communication System) was used for radiographic measurements. A-P radiographic measurements included the main thoracic scoliosis Cobb angle, the distance between cervical seven plumb lines (C7PL), and the centre sacral vertical line. Lateral radiographic measures included C2-C7 cervical lordosis (CL), T1 slope, C2-C7 sagittal vertical axis (C2-7 SVA), T2-T12 thoracic kyphosis (TK), C7-S1 sagittal vertical axis (C7-S1 SVA), proximal junctional angle (PJA), lumbar lordosis, sacral slope, pelvic tilt (PT) and pelvic incidence (PI).

Statistical analysis
All statistical analyses were performed using SPSS Statistics Version 23 (IBM, Armonk, New York). Paired or independent Student t-test was used to analyze continuous data. The χ2 test was used to analyze enumeration data. A P-value < 0.05 was considered statistically significant.
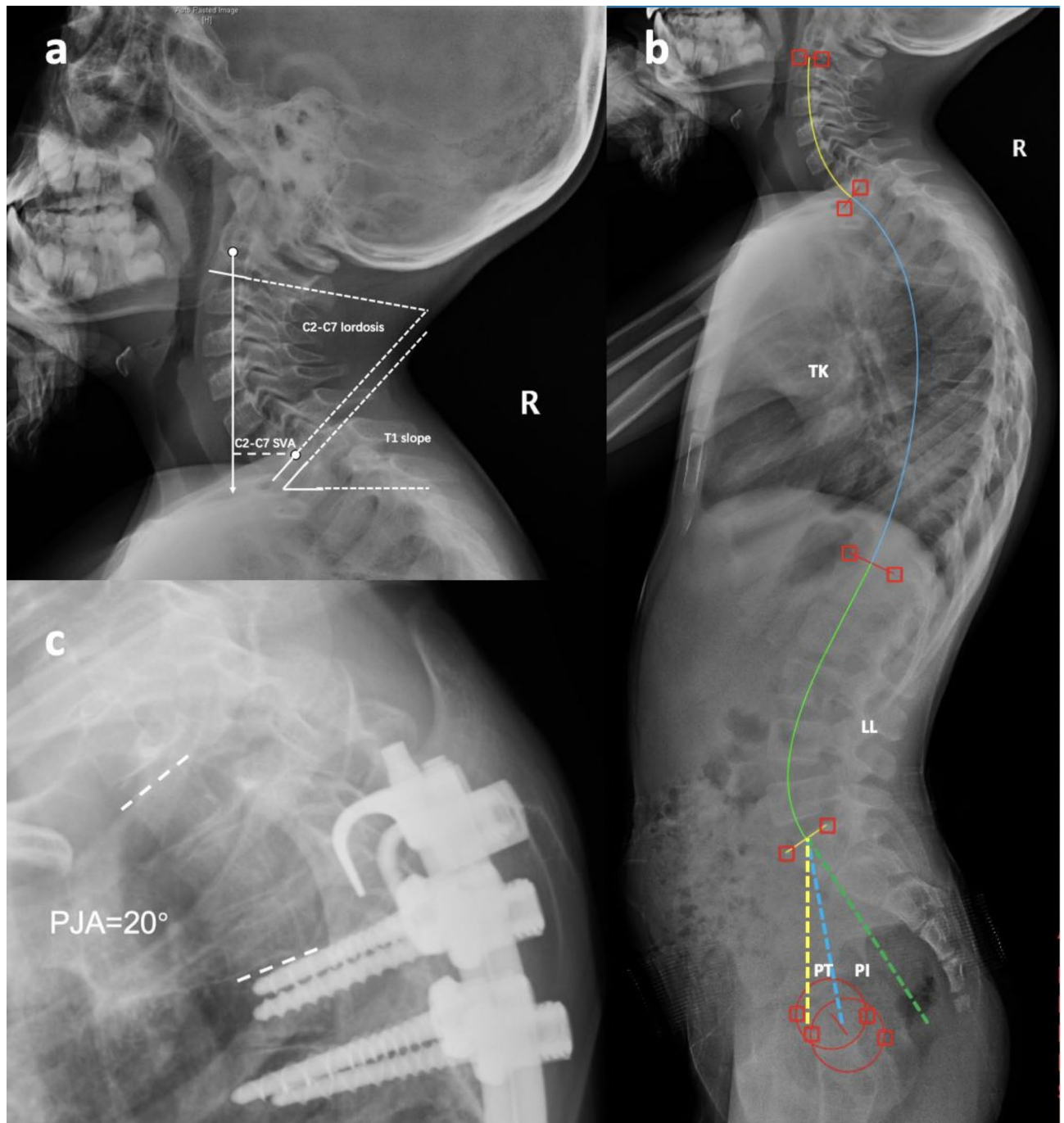
Fig. 1. The measurement demonstration of C2-C7 lordosis, T1 slope and C2-C7 sagittal vertical axis distance (**a**), thoracic kyphosis (TK), lumbar lordosis (LL), pelvic incidence (PI, angle between the green and blue dotted lines) and pelvic tilt (PT, angle between the yellow and blue dotted lines) (**b**). Proximal junctional angle (PJA) is defined as the sagittal Cobb angle between the upper instrumented vertebrae (UIV) and the 2nd vertebrae above the UIV (**c**).

Machine learning construction and testing

Tang et al.[9] showed that C2-7 SVA > 40 mm related to sagittal cervical imbalance resulted in a lower SF-36 score and increased neck pain, and Yokoyama et al.[10] believed that there would be no significance in C2-7SVA with age. C2-7 SVA exceeding 40 mm indicates a severe imbalance of cervical sagittal sequence, affecting patients' postoperative function and quality of life[9]. Therefore, this study defined C2-7 SVA greater than 40 mm as the cervical sagittal imbalance. The sparse additive machine (SAM) classification algorithm, as the state-of-the-art tool in the machine learning community[11], was employed to predict the risk factors of sagittal cervical imbalance after growing-rod surgery. One advantage of SAM is that it can achieve data-driven variable selection.

The features mentioned above relating to clinical, demographic data, surgical information, and radiographic evaluation were extracted and combined into different sets as input parameters of the machine learning model. We randomly divided the datasets into the training set and test set within the ratio of 8:2. We implemented the MAM on MatLab 2016b (MathWorks, Inc., Natick, MA). To obtain the optimized prediction model and avoid over-fitting, we tuned the regularization parameter λ via 10-fold cross-validation in the grid {10^(-4),10^(-3),10^(-2),10^(-1),1,10,100} on the training set. Then, the classification accuracy is evaluated on the test set based on the post-training model.

The interpretable machine learning method, SAM, was introduced by Zhao et al.[11]. The source code has been made available on the R platform under the name SAM (for further details, please refer to the link: https://cran.r-project.org/web//packages/SAM/SAM.pdf). In this manuscript, we enhance this approach by replacing the spline-based hypothesis space with a reproducing kernel Hilbert space. The source code for implementing this method can be accessed through the following link:

https://github.com/yjwangbill/Demo_SAM/tree/db0a347e4459070ae71f9994712b5fbb977967ce/Demo_SAM.

Results

256 EOS patients were reviewed, and 118 were excluded according to the exclusion criteria as shown in the decision tree process (Supplementary material 1). 138 EOS patients, including 96 male and 42 female patients, who met the inclusion criteria, were enrolled in this study.

The demographic data are shown in Table 1. The mean age at the 1st operation was 8.5 ± 2.6ys. The mean follow-up was 38.48 ± 10.87 months. Due to the growth profile and control strategies for spinal deformities, 42 of 138 patients underwent spinal fusion surgery at the last follow-up. Seventy-two patients were diagnosed with idiopathic scoliosis; the remaining 66 patients were with congenital scoliosis, syndromic scoliosis, and neuromuscular scoliosis. Surgical information such as the location of UIV/LIV, type of the UIV, and single/dual growing rod times of lengthening were also recorded. Proximal junctional kyphosis (PJK) would be diagnosed if the PJA was more than 10° or increased by ten compared with the pre-operation[12–15].

After inserting the growing rod, C2-C7 CL, T1 slope, and C2-7 SVA showed no significant change after surgery in the short term. However, in the final follow-up, C2-C7 CL, T1 slope, and C2-7 SVA increased from $-16.93 \pm 10.73°$ to $-35.45 \pm 15.69°$, $27.81 \pm 12.95°$ to $41.86 \pm 19.71°$ and 16.08 ± 11.23 mm to 23.32 ± 13.63 mm respectively ($P < 0.05$) (Fig. 2.) Cervical sagittal alignment changes after the growing rod surgery, as illustrated in Fig. 3.

Patients who were diagnosed with PJK had a larger C2-C7 CL and T1 slope (28.57 ± 12.43 vs. 13.35 ± 7.76, $P < 0.001$; 28.50 ± 11.00 vs. 7.07 ± 13.50, $P < 0.001$). The number of growing rods and location of upper instrumented vertebrae (UIV) had no significant influence on the sagittal cervical parameters. ($P > 0.05$)(Fig. 4). A typical case who suffered a cervical sagittal imbalance caused by PJK is shown in Fig. 5. A case with no PJK and the sagittal cervical alignment kept balanced, as shown in Fig. 6.

In the final follow-up, 98 EOS patients were sagittally balanced ($n = 98$), and 40 were sagittally imbalanced ($n = 40$). The incidence of cervical sagittal malalignment after growing rod surgery during the treatment of EOS was 28.99%. 138 samples were randomly divided into the training set ($n = 111$) and the test set ($n = 27$). We repeated each evaluation f00 times and reported average results (e.g., precision, accuracy, recall) based on different regularization parameters λ in Table 2.

It was found that SAM could achieve better generalization performance when the regularization parameter $\lambda = 10$. In addition, there were 19 features relating to clinical demographic data, surgical information, and radiographic evaluation. In Fig. 7, we plotted the weight for each feature in the estimation process.

The results of the machine learning algorithms showed that the relative weight of the PJK occurrence, improvement of kyphosis, and improvement of T1 slope angle in sagittal cervical imbalance after EOS growing rod surgery was > 0.08, where there was high significance. Growing rod placement time, cervical lordosis

Items	Information
Sample size	$n = 138$
Gender(Male/Female)	96/42
Body mass index(BMI, kg/m2)	16.33 ± 3.85
Diagnose (AIS/CS/syndromic scoliosis / neuromuscular scoliosis.)	72/66
Age at 1st operation	8.48 ± 2.56
Cobb angle (°)	67.00 ± 22.74
Kyphosis (°)	62.93 ± 34.47
UIV(>=T2/< T2)	66/72
LIV(>=L3/< L3)	66/72
Type of the UIV(hood/screw)	132/6
Single/dual growing rod	60/78
PJK(yes/no)	48/90
Times of lengthening	2.78 ± 1.60

Table 1. Basic information.
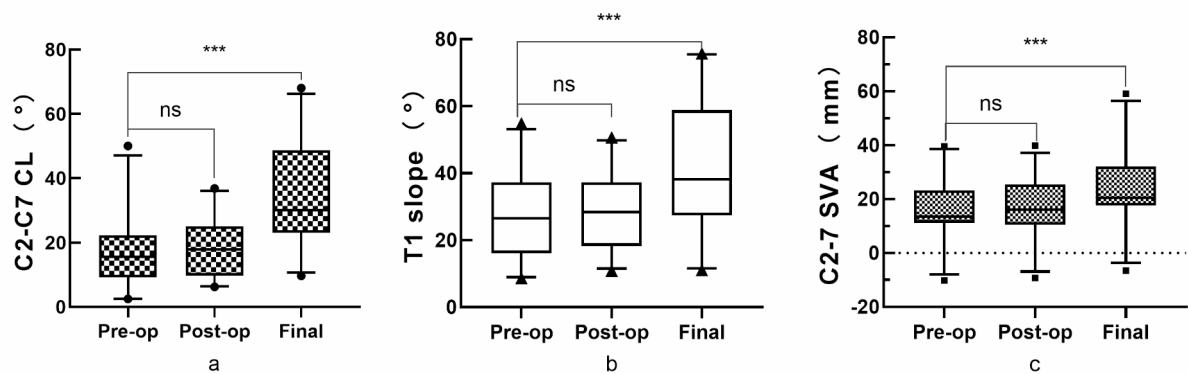
Fig. 2. The comparison of cervical sagittal parameters at pre-operation, post-operation, and final follow-up. (**a**) C2-C7 Cervical lordosis, (**b**) T1 slope, **c** C2-C7 sagittal vertical axis)
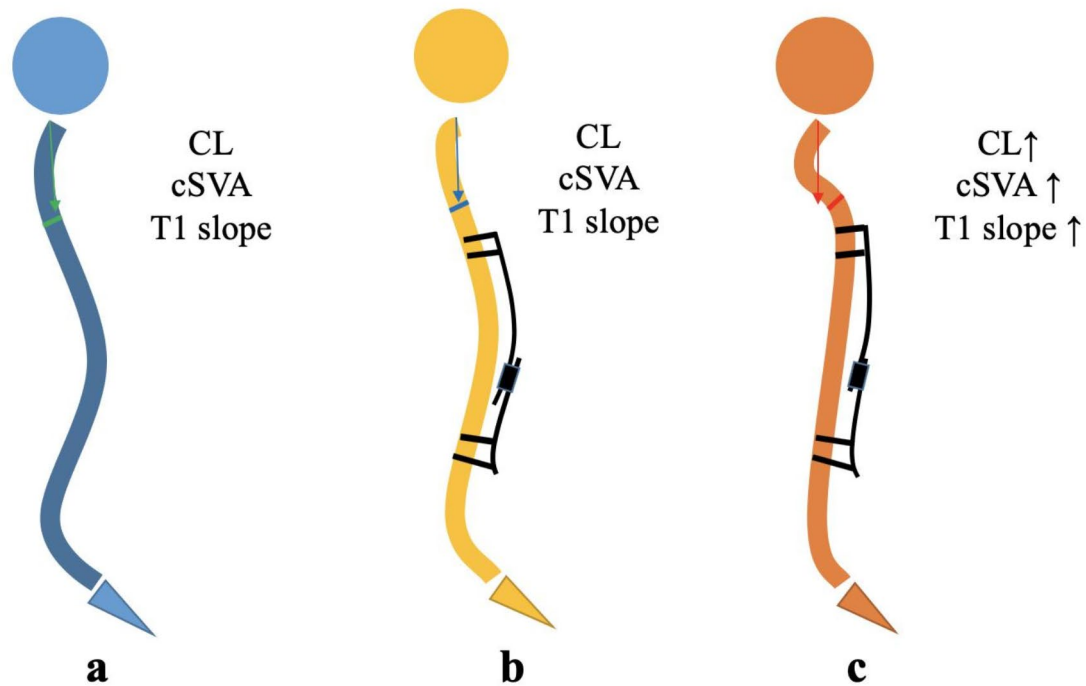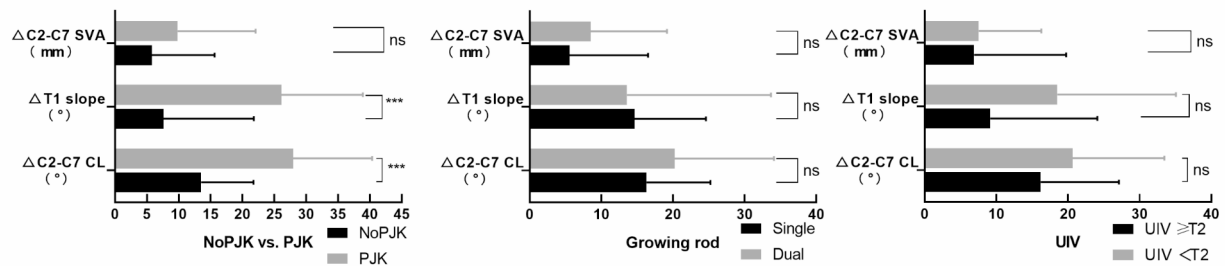

Fig. 3. The illustration of the cervical sagittal balance changes following the growing rod surgery. (**a**) pre-operation, (**b**) post-operation, (**c**) follow-up after lengthening)

changes, and lengthening times are also relatively high in weight, which means that the change of the above features in the forecasting process will significantly affect the risk classification results. Therefore, the occurrence of PJK, more improvement of kyphosis, and T1 slope angle were thought to be the main risk factors of cervical sagittal imbalance.

Discussion

A previous study by Jalai focused on adult scoliosis revealed that postoperative cervical alignment is closely related to health-related quality of life (HRQOL)[16]. Thus, more attention should be paid to cervical alignment in EOS children following growing rod correction. The formation of cervical lordosis in childhood is mainly attributed to the asymmetric development of the anterior and posterior columns of the cervical spine. According to a study by Lee, the average CL (C2-C7) in 181 asymptomatic Asian children, with a mean age of 11.7 years, is $-4.8 \pm 12°$[17].

Fig. 4. The comparison of the impact of surgical strategy and PJK on the sagittal cervical alignment. (PJK: Proximal junctional kyphosis; UIV: Upper instrumented vertebrae)
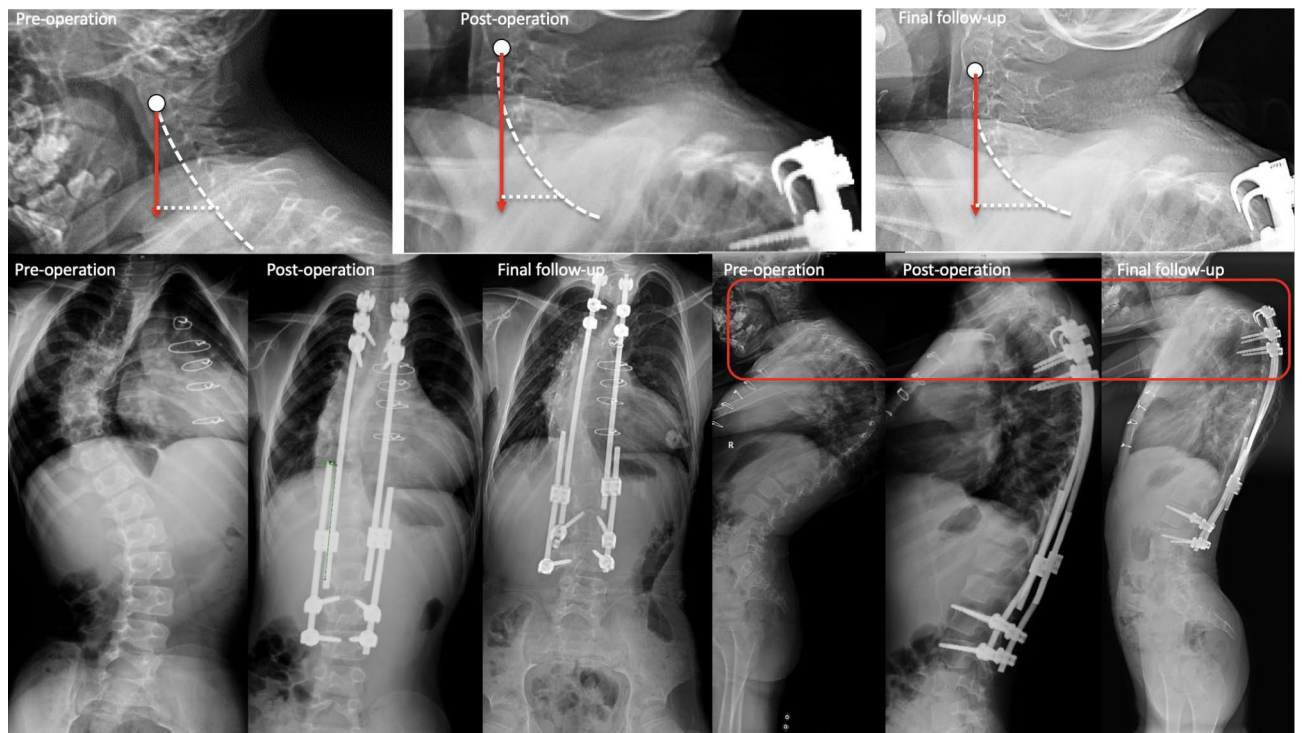
Fig. 5. During growing rod treatment, the cervical sagittal balance changes in the patient with PJK. (It is an 8-year-old male patient diagnosed with idiopathic EOS. After the 3rd distraction, scoliosis and hyperkyphosis are corrected well. In the final follow-up, he has PJK above the growing rod. Sagittal cervical alignment change: C2-C7 CL increases from 24.6° to 62.7°, T1 slope increases from 47.2° to 67.7°, and C2-C7 SVA increases from 24.3 mm to 34.2 mm.)

The CL of the EOS patients included in this group is significantly bigger (-16.93 ± 10.73° vs. -4.8 ± 12°) than that of the asymptomatic Asian children, but at a slightly younger age (8.5 vs. 11.7). And the CL increases significantly to -35.45 ± 15.69°, at the last follow-up. This change in cervical alignment differs from adolescent scoliosis after fusion correction, in which the CL decreases and even becomes cervical kyphosis. The leading cause of this phenomenon is that the growing rod increases the focal kyphosis on the proximal junctional area, which leads to a compensatory increase in CL, especially for patients with postoperative PJK whose CL will increase more dramatically. In the meantime, CL is still developing before ten years old, which can also be considered a potential CL-increasing mechanism.

T1 slope is smaller in adolescent idiopathic scoliosis (AIS) patients due to the hypokyphosis compared with asymptomatic normal adolescents based on the study of Hiyama[18], and the mean value of T1 slope is 11.4 ± 9.4° in AIS group and 17.8 ± 7.9 ° in the control group respectively. Compared with the data of AIS, the T1 slope in EOS patients from this study has a noticeable increase after the operation, especially at the latest follow-up (27.81 ± 12.95°at pre-operation, 28.24 ± 10.90° at post-operation, and 41.86 ± 19.71° at the final follow-up). Pepke[19] believed that the angle of the T1 slope has a significant influence on the sagittal alignment of the lower
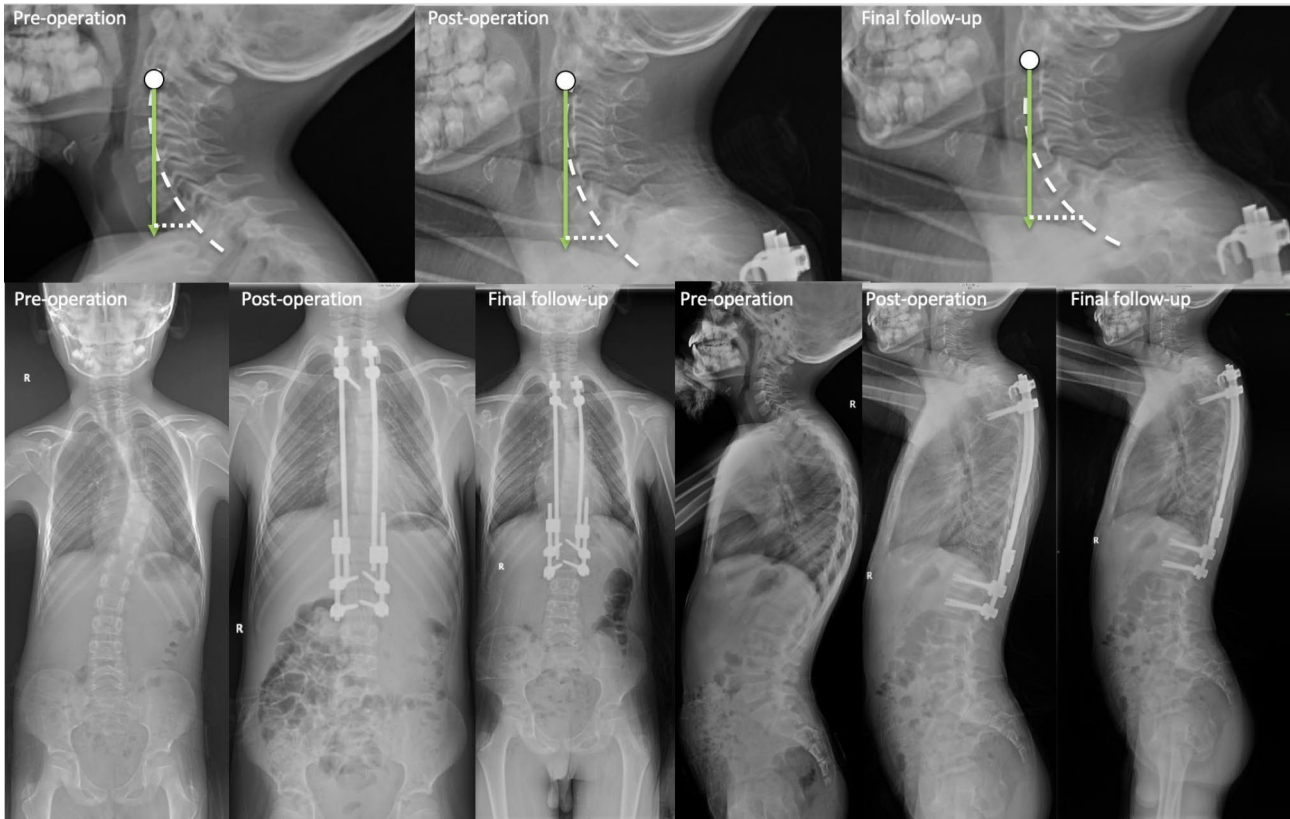
Fig. 6. During growing rod treatment, the cervical sagittal balance changes in the patient without PJK. (It is a 10-year-old male patient diagnosed with idiopathic EOS. After the 2nd distraction, scoliosis and hyperkyphosis are corrected well. In the final follow-up, he does not have PJK above the growing rod. Sagittal cervical alignment change: C2-C7 CL increases from 57.9° to 62.9°, T1 slope increases from 48.1° to 57.4°, and C2-C7 SVA increases from 22.5 mm to 24.5 mm.)

	Precision	Accuracy	Recall
$\lambda = 0.0001$	0.7579	0.6855	0.5814
$\lambda = 0.001$	0.7230	0.6806	0.5918
$\lambda = 0.01$	0.7542	0.6916	0.5966
$\lambda = 0.1$	0.7447	0.6797	0.6005
$\lambda = 1$	0.7571	0.6891	0.5882
$\lambda = 10$	0.7644	0.7001	0.5995
$\lambda = 100$	0.7332	0.6672	0.6013

Table 2. The average results based on different regularization parameter.

cervical vertebra and that the increase of the T1 slope will lead to an increase in cervical lordosis. Lee[20] also proposed that the T1 slope can be used as the parameter to predict the physiological alignment of the cervical spine. Pesenti's retrospective study[21] showed that the increase of T1 slope (10.2° pre-op vs. 18.2° post-op) is a good indicator of postoperative changes for regional (cervical lordosis and thoracic kyphosis) and complete spinal sagittal alignment after surgery. However, the T1 slope in this study increases beyond the normal range (from $27.81 \pm 12.95°$ to $41.86 \pm 19.71°$). Similar to the mechanism of CL increase, the increase of the proximal junctional angle after growing rod surgery makes T1 tilt more.

As the sacral slope is one of the main risk factors of lumbar spondylolisthesis[22], the excessive increase of T1 slope may increase the possibility of lower cervical spine instability and even cervical spondylolisthesis. Therefore, for these patients, we should pay closer attention and follow up to observe if there will be long-term cervical instability. Instructing the patients to focus on the shape of the neck and back is also essential, and wearing a cervicothoracic brace when necessary. In the final fusion surgery, efforts should be made to correct the PJK by Ponte osteotomy in the junctional area for severe hyperkyphotic cases and reduce the T1 tilt as much as possible.
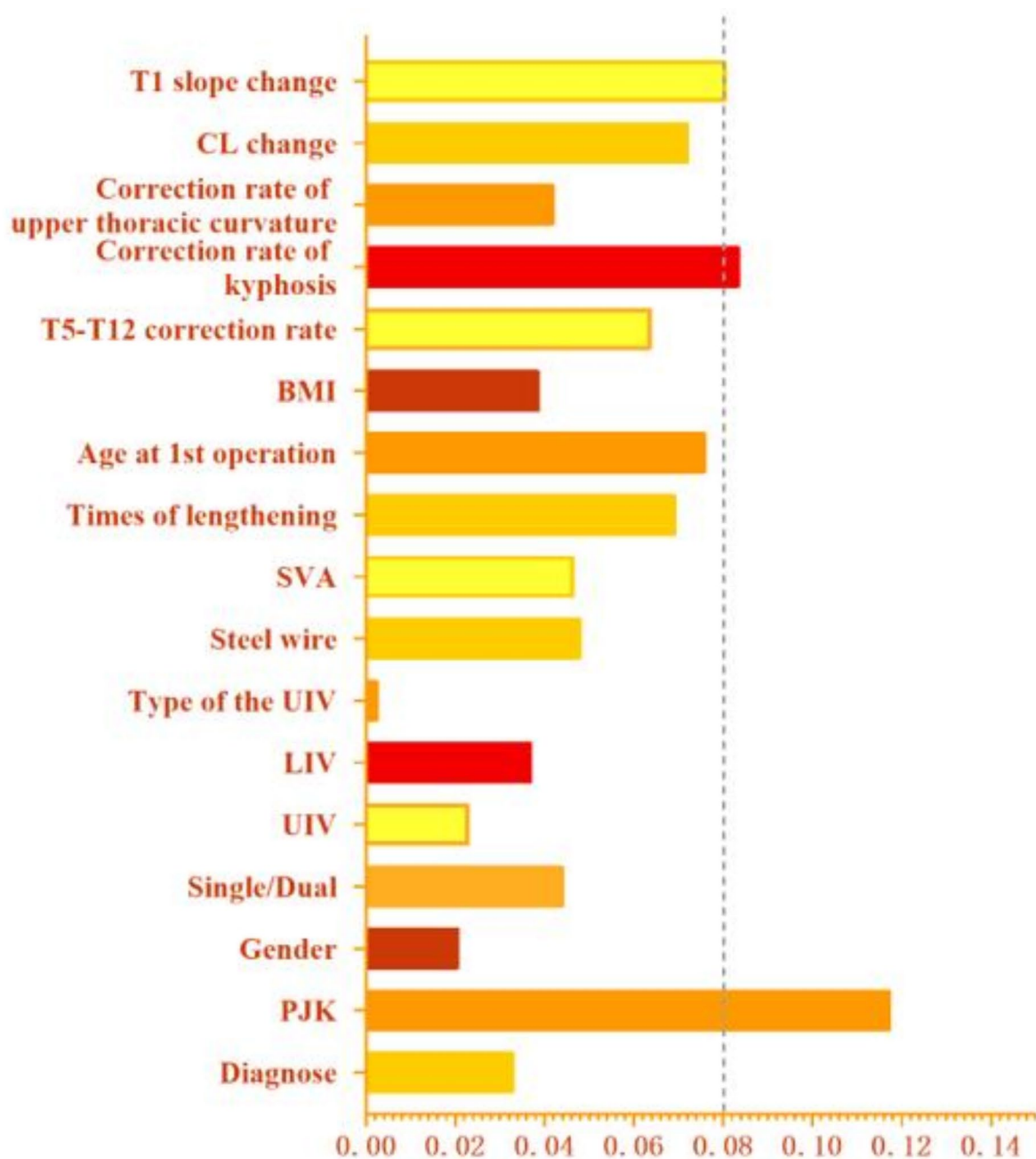
Fig. 7. The weight for each feature in the estimation of risk factors of sagittal cervical imbalance after growing-rod surgery.

C2-C7 SVA is a valuable parameter to assess cervical sagittal alignment[7]. It was proved that high C2-C7 SVA is one of the independent predictors of cervical disability index score (NDI) before surgery in the study of Iyer[23]. C2-C7 SVA was also proved to be correlated with the SRS-22 scale of AIS patients in the study of Youn[24]. Therefore, C2-C7 SVA can be an essential parameter for scoliosis patients' evaluation. In this study, 42 patients have C2-C7 SVA imbalance after the growing rod surgery, and the alignment is also affected by the upper thoracic junctional alignment above the growing rod. When PJK occurs after the growing rod surgery, T1 vertebrae tilt much more than the pre-operation, leading the cervical spine to tip forward. On the other hand, the back-extension muscles of the cervical spine are relatively weak in children[25]. Thus, it is challenging to restore cervical spine alignment through muscle compensation.

With the development of artificial intelligence, machine learning became a robust set of technologies because of the three main tasks: classification, regression, and clustering[26]. There is a great advantage in using newly generated information to improve their predictive capability on machine learning algorithms[27]. SAM is a functional version of the support vector machine combined with sparse additive modelling, as reported by Zhao

et al. in 2012[11]. Along with the computational algorithms, SAM can provide another recipe for high dimensional, small sample size, and complex data analysis, which is computationally more efficient and amenable to theoretical analysis. Applying the machine learning statistical analysis method made the analysis results of this study more reliable.

Until ten years, the cervical spine gradually remained balanced and remained almost unchanged after that[28]. The curvature of children's cervical spine changes as it develops, which may explain why the extended time with the growing rod was mainly a risk factor for sagittal cervical imbalance after growing-rod surgery. It can be seen that the cervical alignment was closely related to PJK after the growing rod surgery. PJK is a common long-term complication in EOS patients who underwent growing rod surgery with an incidence of 28% based on our previous study[29]. It develops for multiple reasons, including posterior ligament complex disruption, junctional disk degeneration, vertebrae fracture, and instrumentation failure[30,31]. From a biomechanical perspective, the stress over the junctional area increases postoperatively, which may accelerate the degeneration of the disk and ligament. The UIV distal to T2, LIV distal to L3, and postoperative upper thoracic curve of more than 50° are the risk factors for PJK[29,32]. Therefore, selecting the fixation vertebrae properly and correcting the hyperkyphosis will help to reduce cervical imbalance and keep the cervical alignment healthy during the growing rod surgery treatment.

Changes in the cervical spine alignment should be addressed when the growth-friendly technique is applied to correct the EOS. PJK after growing rod surgery is difficult to avoid, with an incidence of 17-28% altogether[29,32–34]. The kyphotic change in the cervicothoracic area increases the T1 slope, then the cervical lordosis increases and the cervical spine is in danger of being out of balance. In turn, the imbalance of cervical spine sequences will aggravate the PJK in EOS patients[35]. Ways to prevent this vicious cycle include selecting the UIV and LIV properly in the preoperative plan and protecting the posterior ligamentous complex (PLC) of the junctional area intraoperatively to decrease the incidence of PJK as much as possible. The risk of neural injury during growing rod adjustments for EOS is low but requires vigilant monitoring and careful surgical technique. The use of neuromonitoring is justified, particularly during primary implantation and exchange surgeries, to minimize the risk of neural injury. In addition, the indication and timing for growing rod surgery should be adequately controlled to avoid surgical intervention.

We acknowledge several study limitations of this study. Firstly, it was a retrospective study, which limits the reliability of the evidence. Most patients with EOS come from high altitude and remote mountainous areas in China, which causes great difficulties for functional follow-up of patients. Secondly, the sample size was not big enough, and all cases were selected from a single institution, which inspired us to carry out multicenter research and provide more convincing evidence. Due to the poor imaging quality in the follow-up data, the number of included patients was small, and it was difficult to make a comparative analysis of postoperative changes in cervical sagittal position sequence in more EOS patients who received growth rod treatment. We believe that, in terms of EOS research, our centre in China possesses a sufficiently large cohort and patient base, which also paves the way for future studies with even larger sample sizes. Thirdly, most EOS patients come from remote mountainous areas of China, making it very difficult to assess their quality of life and analyze the correlation between cervical spine sequence changes and clinical efficacy.

Conclusions
Cervical sagittal alignment was significantly affected by the growing rod surgery in EOS. Postoperative PJK and the early insertion of the growing rod would lead to a higher incidence of cervical sagittal imbalance.

Data availability
The datasets generated and analyzed during the current study are not publicly available due to official requirements for the author's doctoral dissertation in writing but are available from the corresponding author on reasonable request with ease.

References
1. Zhang, Y. B. & Zhang, J. G. Treatment of early-onset scoliosis: Techniques, indications, and complications. *Chin. Med. J. (Engl).* **133**, 351–357 (2020).
2. Davies, G. & Reid, L. Effect of scoliosis on growth of Alveoli and pulmonary arteries and on right ventricle. *Arch. Dis. Child.* **46**, 623–632 (1971).
3. Yang, S., Andras, L. M., Redding, G. J. & Skaggs, D. L. Early-onset scoliosis: A review of history, current treatment, and future directions. *Pediatrics* **137**(1), e20150709. https://doi.org/10.1542/peds.2015-0709 (2016).
4. Johnson, A. N. & Lark, R. K. Current concepts in the treatment of early onset scoliosis. *J. Clin. Med.* **13**(15), 4472. https://doi.org/10.3390/jcm13154472 (2024).
5. Smith, J. T., Johnston, C., Skaggs, D., Flynn, J. & Vitale, M. A new classification system to report complications in growing spine surgery: A Multicenter Consensus Study. *J. Pediatr. Orthop.* **35**, 798–803 (2015).
6. Fukase, Y. et al. A case of early onset scoliosis with trisomy 1Q and monosomy 21Q. *Spine surg. Relat. Res.* **8**, 654–658 (2024).
7. Scheer, J. K. et al. Alignment, classification, clinical evaluation, and Surgical Treatment for adult cervical deformity: A complete guide. *Neurosurgery* **88**, 864–883 (2021).
8. Piantoni, L. et al. Proximal junction kyphosis after posterior spinal Fusion for early-onset scoliosis. *Spine Deform.* **8**, 311–316 (2020).
9. Tang, J. A. et al. The impact of standing regional cervical sagittal alignment on outcomes in posterior cervical fusion surgery. *Neurosurgery*. **76** (Suppl 1), S14-S21, discussion S21 (2015).
10. Yokoyama, K. et al. Age-related variations in global spinal alignment and sagittal balance in asymptomatic Japanese adults. *Neurol. Res.* **39**, 414–418 (2017).

11. Zhao, T. & Liu, H. Sparse additive machine. In *Appearing in Proceedings of the 15th International Conference on Artificial Intelligence and Statistics*. Canary Islands (2012).
12. Glattes, R. C. et al. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: Incidence, outcomes, and risk factor analysis. *Spine* **30**, 1643–1649 (2005).
13. Helgeson, M. D. et al. Evaluation of proximal junctional kyphosis in adolescent idiopathic scoliosis following pedicle screw, hook, or hybrid instrumentation. *Spine* **35**, 177–181 (2010).
14. Yagi, M., Akilah, K. B., Boachie-Adjei, O. & Incidence risk factors and classification of proximal junctional kyphosis: Surgical outcomes review of adult idiopathic scoliosis. *Spine* **36**, E60–E68 (2011).
15. Hart, R. et al. Identification of decision criteria for revision surgery among patients with proximal junctional failure after surgical treatment of spinal deformity. *Spine* **38**, E1223–E1227 (2013).
16. Jalai, C. M. et al. A comparative analysis of the prevalence and characteristics of cervical malalignment in adults presenting with thoracolumbar spine deformity based on variations in treatment approach over 2 years. *Eur. Spine J.* **25**, 2423–2432 (2016).
17. Lee, C. S. et al. Analysis of Sagittal spinal alignment in 181 asymptomatic children. *J. Spinal Disord. Tech.* **25**, E259–E263 (2012).
18. Hiyama, A. et al. Sagittal alignment of the cervical spine in adolescent idiopathic scoliosis: A comparative study of 42 adolescents with idiopathic scoliosis and 24 normal adolescents. *Eur. Spine J.* **25**, 3226–3233 (2016).
19. Pepke, W. et al. Cervical spine alignment following surgery for adolescent idiopathic scoliosis (Ais): A pre-to-post analysis of 81 patients. *BMC Surg.* **19**, 7 (2019).
20. Lee, S. H. et al. The influence of thoracic inlet alignment on the craniocervical sagittal balance in asymptomatic adults. *J. Spinal Disord. Tech.* **25**, E41–E47 (2012).
21. Pesenti, S. et al. Interest of T1 parameters for sagittal alignment evaluation of adolescent idiopathic scoliosis patients. *Eur. Spine J.* **25**, 424–429 (2016).
22. Chen, Q. et al. Degenerative spondylolisthesis in the fifth lumbar vertebra and radiographic parameters: A correlation analysis. *Clin. Spine Surg.* **30**, E1233–E1238 (2017).
23. Iyer, S. et al. Impact of cervical sagittal alignment parameters on neck disability. *Spine* **41**, 371–377 (2016).
24. Youn, M. S. et al. Relationship between cervical sagittal alignment and health-related quality of life in adolescent idiopathic scoliosis. *Eur. Spine J.* **25**, 3114–3119 (2016).
25. McKay, M. J. et al. Normative reference values for strength and flexibility of 1,000 children and adults. *Neurology* **88**, 36–43 (2017).
26. Buchlak, Q. D. et al. Machine learning applications to clinical decision support in neurosurgery: An artificial intelligence augmented systematic review. *Neurosurg. Rev.* **43**(5), 1235–1253. https://doi.org/10.1007/s10143-019-01163-8 (2020).
27. Kim, J. S. et al. Predicting Surgical complications in patients undergoing elective adult spinal deformity procedures using machine learning. *Spine Deform.* **6**, 762–770 (2018).
28. Kasai, T., Ikata, T., Katoh, S., Miyake, R. & Tsubo, M. Growth of the cervical spine with special reference to its lordosis and mobility. *Spine* **21**, 2067–2073 (1996).
29. Pan, A., Hai, Y., Yang, J., Zhang, Y. & Zhang, Y. Upper Instrumented vertebrae distal to T2 leads to a higher incidence of proximal junctional kyphosis during growing-rod treatment for early onset scoliosis. *Clin. Spine Surg.* **31**, E337–E341 (2018).
30. Rhee, J. M. et al. Sagittal plane analysis of adolescent idiopathic scoliosis: The effect of anterior versus posterior instrumentation. *Spine* **27**, 2350–2356 (2002).
31. Ferrero, E. et al. Proximal junctional kyphosis in thoracic adolescent idiopathic scoliosis: Risk factors and compensatory mechanisms in a Multicenter National Cohort. *Eur. Spine J.* **27**, 2241–2250 (2018).
32. Watanabe, K. et al. Risk factors for proximal junctional kyphosis associated with dual-rod growing-rod surgery for early-onset scoliosis. *Clin. Spine Surg.* **29**, E428–E433 (2016).
33. El-Hawary, R. et al. What is the risk of developing proximal junctional kyphosis during growth friendly treatments for early-onset scoliosis? *J. Pediatr. Orthop.* **37**, 86–91 (2017).
34. Carender, C. N. et al. Low pelvic incidence is associated with proximal junctional kyphosis in patients treated with growing rods. *Spine* **41**, 792–797 (2016).
35. Passias, P. G. et al. Cervical alignment changes in patients developing proximal junctional kyphosis following surgical correction of adult spinal deformity. *Neurosurgery* **83**, 675–682 (2018).

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Author contributions

BH: acquisition and analysis of data, drafting of the article, and statistical analysis; JH: statistical analysis, drafting of the article, and machine learning algorithms analysis; AP: design, acquisition, and analysis of data, drafting of the article, and statistical analysis; YW: machine learning algorithms analysis; YH: design, review, and revision of the final manuscript, technical and administrative support. All author(s) read and approved the final manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Ethical approval

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Consent for publication

We state that we have consent for publication.

Consent to participate

We state that we have consented to participate.

Additional information

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