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REVIEW ARTICLE

Selective fusion for adolescent idiopathic scoliosis: a review of current operative strategy

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Abstract Selective fusion of thoracic and thoracolumbar/lumbar curves in adolescent idiopathic scoliosis is a concept critically debated in the literature. While some surgeons strongly believe that a more rigid and straighter spine provides predictably excellent outcomes, some surgeons recommend a mobile and less straight spine. This topic is a crucial part of surgical treatment of idiopathic scoliosis, particularly in young patients who will deal with the stress of the fusion mass at the proximal and distal junctions over many years. This study will review the literature on various aspects of selective fusion.

Keywords Selective fusion · Adolescent idiopathic scoliosis · Spinal fusion · Selective thoracic fusion · Selective thoracolumbar/lumbar fusion · Spinal deformity

Introduction

The surgical treatment of adolescent idiopathic scoliosis (AIS) has made remarkable progress since the development of the Harrington rod in the late 1950s [1]. As new instrumentation was introduced over the next few decades, the ability to correct patients' curves improved significantly. The technology has changed, but the goals of surgery for AIS remain the same: (1) halt curve progression and correct deformity, (2) maintain a balanced spine in the coronal and sagittal planes, (3) preserve as many mobile spinal segments as possible, and, (4) prevent surgical complications such as junctional kyphosis, adding-on, and revision surgery [2–11]. Since the publication of the landmark article by King et al. [12], some double major curves have been identified as containing a structural and a compensatory component. The King Type II curve is known as the "false double major" pattern, because the lumbar curve shows less magnitude and more flexibility on side-bending films which suggests that it is a compensatory curve present only to maintain coronal balance in the setting of a fixed thoracic curve. The King Type II curve was later reclassified by Lenke et al. [13–15] as Lenke 1C, 2C, 3C, and 4C curves. Controversy exists over the treatment of the compensatory lumbar curve in King Type II curves [15, 16]. Moe recommended selective fusion of the thoracic curve because the lumbar curve in a King Type II curve would undergo spontaneous correction following selective thoracic fusion [4, 12, 17–21]. Recent studies have shown that more flexible compensatory curves are able to correct spontaneously after fusion of the structural curve [3–5, 7, 10, 17, 18, 22–27]. As pedicle screws began to be used in the thoracic spine, studies showed superior curve correction with all pedicle screw constructs due to the three column fixation of pedicle screws and greater ability to translate and derotate the spine [5, 28]. Dobbs et al. [3] in 2006 found that pedicle screws allowed for better curve correction than hooks for selective thoracic fusion. The majority of spinal deformity surgeons believe that a balanced and mobile lumbar spine without progression of the lumbar curve is better than a straight and stiff lumbar spine. They feel comfortable with selective fusions for a more mobile and less corrected spine because it is also possible to extend the selective thoracic fusion to the lumbar spine in instances when the lumbar curve is progressing, although the rate of progression requiring fusion is very low in the current published literature. However, some advocated for long fusions including the major thoracic curve and compensatory lumbar curve from the upper

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thoracic spine to either L3 or L4 for better correction of both curves and also to diminish the risk of postoperative coronal decompensation, progression of lumbar curve, adding-on, junctional kyphosis, and eventual revision surgery. Selective fusion is a concept that has developed over this controversy and is defined in this review as isolated thoracic fusion with Lenke 1C, 2C, some 3C, and some 4C curves as well as isolated thoracolumbar/lumbar curves in Lenke 5C and some 6C curves.

One of the key features of the Lenke classification system is the ability for the classification to guide surgeons in treatment. Each Lenke curve type indicates which part of the spine should undergo fusions. In patients with Lenke Type 1C curves, only the thoracic curve should undergo fusion by classification. Yet many surgeons prefer to fuse both curves. One study showed that selective thoracic fusion was performed in 62% of patients with Lenke 1C curves [14]. This study found that both the thoracic and lumbar curves are fused in 38% of the Lenke 1C curves. This result is contradictory to the recommendations provided by the Lenke classification and thus the Lenke lumbar C modifier was termed a “rule breaker”. Another study by Newton et al. [29] showed that five AIS centers in the United States varied between 6 and 67% for selective thoracic fusions for Lenke 1C curves.

The difficulty now lies in determining which patients should undergo selective fusion and which vertebrae should be included in the fusion. There are many parameters that must be considered when evaluating a patient for selective fusion of either the main thoracic or thoracolumbar/lumbar curves including patient lifestyle and expectation as well as guidelines for selective fusion, fusion levels, amount of curve correction, and potential complications. The purpose of this study is to review the literature to determine the guidelines for selective fusion in adolescent idiopathic scoliosis.

Criteria of selective thoracic fusion

The goal of selective thoracic fusions in Lenke 1C, 2C, 3C, and 4C curves is to allow for as many mobile vertebral segments as possible while still achieving spontaneous correction of minor curves [10]. The King–Moe Type II curve is an s-shaped double curve pattern that comprised right thoracic and left lumbar curves which cross the midline (the apical vertebrae of each curve are past the midline) and the thoracic curve is equal to or larger and more rigid than the lumbar curve [12]. Moe recommended selective thoracic fusion if the lumbar curve is more flexible and smaller. Lenke and Bridwell [30] reported that the King–Moe definition of a Type II curve was not sufficient to recommend selective thoracic fusion and delineated more strict radiographic guidelines for selective thoracic fusion. Their criteria included relative apical vertebral translation, apical vertebral rotation, Cobb angle, and flexibility of the two curves as well as sagittal plane assessment of the thoracolumbar junction.

The most important factors to decide whether or not to perform selective thoracic fusion consist of patient lifestyle and clinical patient status including activity level, age, and preference to sports. Some patients such as professional dancers or athletes require more lumbar flexibility for their activity and thus require selective thoracic fusion if indicated [17, 22]. The patient and family need to understand the potential for lumbar curve progression, junctional problems, and revision surgery to extend the fusion. Physical examination such as Adams forward bending test is very important. Thoracic rotational prominence should be larger than the lumbar prominence with a scoliometer. Flexibility on thumb abduction testing is also important. If a patient is very flexible, a selective fusion may not be a good choice.

Radiographic criteria proposed by Lenke et al. are to be considered more when evaluating a patient for possible selective thoracic fusion. The thoracic apical vertebral translation (AVT) is the distance between the C-7 plumb line and the center of the apical vertebral body of the thoracic curve (Fig. 1). The thoracolumbar/lumbar AVT is the distance between the center of the apical vertebral body of the thoracolumbar/lumbar curve and the center sacral vertebral line. A ratio of thoracic AVT to thoracolumbar/lumbar AVT larger than 1.2 indicates a more translated (20% or more) thoracic curve that may be treated with selective thoracic fusion [10, 22, 31, 32]. The second factor that helps to determine if selective thoracic fusion is feasible is apical vertebral rotation (AVR). This is based on the Nash–Moe grading for vertebral rotation based on the radiographic pedicle appearance of the thoracic or thoracolumbar/lumbar apical vertebrae [33]. A ratio of thoracic AVR to thoracolumbar/lumbar AVR greater than 1.2 suggests that the thoracic curve is more rotated (20% or more) than the thoracolumbar/lumbar curve, and thus may undergo selective thoracic fusion [10, 22, 31, 32]. This radiographic rotation may be replaced by a scoliometric measurement mentioned above. The third factor is the magnitude of the curves on Cobb measurements. The thoracic Cobb angle must be larger (20% or more) than the thoracolumbar/lumbar Cobb angle by a suggested ratio of 1.2 [10, 22, 31, 32]. The lumbar curve which is nonstructural with side bending to less than 25° and a sagittal kyphosis T10–L2 of less than 20° is a better candidate [13, 16]. A more flexible thoracolumbar/lumbar curve is one that will spontaneously correct upon selective fusion of the thoracic spine [22, 31]. However, Behensky et al. [34] showed relatively non-flexible thoracolumbar/lumbar

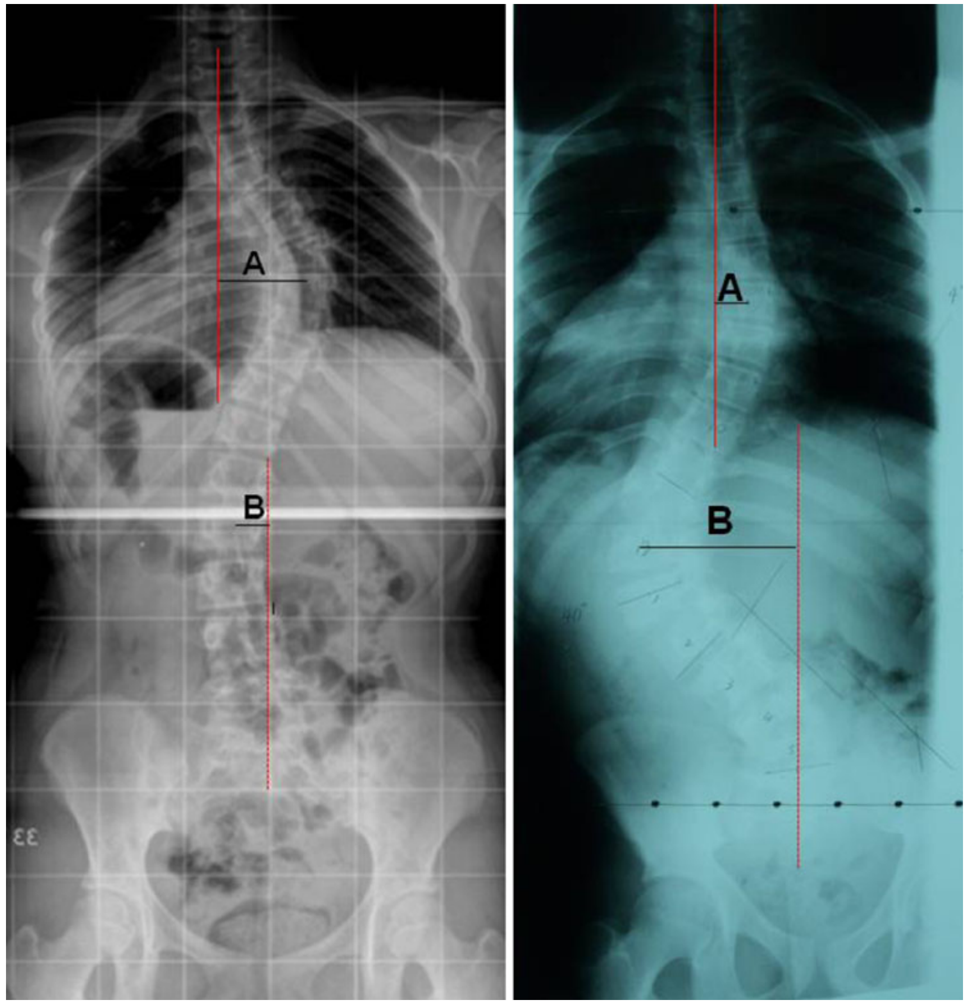

Fig. 1 The thoracic apical vertebral translation (*A*) is the distance between the center of the thoracic apical vertebra (*A*) and the C7 plumb line (*solid line*). The lumbar apical vertebral translation (*B*) is the distance between the center of the lumbar apical vertebra and central sacral vertical line (*dashed line*)

curves with side bending to more than 25°, Lenke 3C curves, spontaneously correct. They found that of 21 patients in Lenke 3C curves who met 2 or 3 out of 3 of the above criteria had good postoperative coronal balance and outcomes. They did not perform selective fusion in patients with lumbar Cobb angles greater than 60°. Relative ratio of AVT is known to be the most important factor for good outcomes among the three radiographic parameters. Selective fusion of the thoracic spine is possible in Lenke 3C curves if AVT, AVR or Cobb ratio is larger [34]. A fourth variable to consider is the sagittal plane balance. The thoracolumbar junctional angle between T10 and L2 should be less than 10°. The sagittal disc angle below the instrumented vertebrae should be lordotic [15, 30]. Skeletal maturity is also important. Closure of the triradiate cartilage is very important in preventing postoperative progression of the lumbar spine and junctional decompensation [31].

These various factors for selective fusion of thoracic curves are summarized in Table 1. The level of evidence for these recommendations are based on mostly level IV evidence case series studies that report outcomes after treatment as sited above. There are no studies that compare outcomes to controls nor are there randomized control trials.

Determination of fusion levels for selective thoracic fusion

Once a patient is determined for selective fusion, the next step is to determine which levels need to be fused. Selection of the ideal lowest instrumented vertebrae (LIV) is crucial in preventing distal junctional problems such as adding-on or distal junctional kyphosis. Yet it is still important to retain as many mobile vertebral segments as possible. Goldstein [35] noted that the fusion should often be extended to the neutral vertebra to prevent future adding-on of the curve. King et al. [25] identified the stable and neutral vertebra as the appropriate area to end a fusion for false double major curve. The majority of studies have shown satisfactory outcomes when the LIV is at the stable

Table 1 Factors for selective fusion of thoracic curves

Category	Criteria	Notes
Candidates	Lenke 1C, 2C, 3C, 4C	
Clinical parameters	Lifestyle and activity level	
	Thoracic rotational prominence > lumbar prominence	
	Soft tissue flexibility: thumb abduction test	
Radiographic parameters		
Coronal plane ratio criteria	$\frac{\text{AVT thoracic}}{\text{AVTthoracolumbar/lumbar}} > 1.2$	Possible if AVT criteria only Better if 2 or 3 criteria met
	$\frac{\text{AVR thoracic}}{\text{AVRthoracolumbar/lumbar}} > 1.2$	
	$\frac{\text{Thoracic Cobb angle}}{\text{Thoracolumbar/lumbarCobbangle}} > 1.2$	
Sagittal plane criteria	Thoracolumbar (T10–L2) kyphosis < 10°	
	Sagittal disc angle below LIV—lordosis	
Skeletal maturity	Triradiate cartilage—closed	
Additional criteria	TL/L side bender < 25°	Possible if TL/L side bender >25° if more criteria met
	TL/L curve < 60°	
	CSL touches thoracic LEV or below	

AVT apical vertebral translation, *AVR* apical vertebral rotation, *LIV* lowest instrumented vertebra, *TL/L* thoracolumbar/lumbar, *LEV* lower end vertebrae

and neutral vertebra [3, 5, 7, 17, 20, 36, 37]. One study showed a significantly increased risk of lumbar decompensation when the fusion did not end at the stable and neutral vertebra, and decompensation occurred at a rate of 22% [4].

There are some patients with Lenke 1C curves that have a significant pre-operative trunk shift toward the left side. This means that the stable vertebra by the center sacral line is located around the thoracic apex and ending the fusion construct around the thoracic apex would lead to poor outcomes. In this situation, Goldstein's recommendation of ending the fusion at neutral or 1 vertebra distal to the neutral vertebra may be an option for selective thoracic fusion, not to extend the fusion to the lower lumbar spine and retain a mobile lumbar spine.

Other factors that contribute to LIV selection include the sagittal balance and patient skeletal maturity. A sagittal kyphosis at the thoracolumbar junction (T10–L2) of less than 20° and a lordotic disc angle below the LIV is important to prevent distal junctional kyphosis [10, 38]. Additionally, closure of the triradiate cartilage is important to prevent adding-on and distal junctional problems [36].

Selection of the uppermost instrumented vertebra (UIV) is also important for shoulder balance and proximal junctional kyphosis. The important pre-operative factors are standing shoulder balance (left high, level, and right high), structurality of the proximal thoracic curve, sagittal thoracic kyphosis at T2–T5, and instrumentation technique. If the left shoulder is high, then the UIV should be T2 in Lenke 2C curves or 2 vertebra proximal to the upper end vertebra in Lenke 1C curves [39]. Preservation of the thoracic kyphosis or an intra-operative increase of thoracic kyphosis is important to prevent proximal junctional kyphosis [40]. Surgical technique is also an important component to prevent junctional kyphosis. Distraction of the concave side of the curve rather than compression of convex side at the UIV is better to prevent proximal junctional kyphosis [41].

The amount of correction for selective thoracic fusion

Curve correction is another aspect of selective thoracic fusion that is frequently debated. Although spontaneous lumbar curve correction occurs consistently following a selective thoracic spinal fusion, the degree of correction is somewhat unpredictable. Previous studies have shown that over correction of the thoracic curve is related to progression of the lumbar curve below a selective thoracic fusion [42, 43] due to lack of compensatory lumbar curve correction [30, 44–49]. It has been hypothesized that the unfused lumbar compensatory curve cannot compensate for excessive correction of the main thoracic curve and this therefore results in coronal decompensation [8, 50, 51]. Richards et al. [8] reported less postoperative spontaneous correction of the lumbar curves than shown on pre-operative flexibility radiographs (27 compared to 70%, respectively) in King Type II curves with Cotrel–Dubousset instrumentation. The thoracic curve was corrected to 48% of pre-operative curve in this study, which may explain why the lumbar curve was unable to spontaneously correct more than 27%. Roye et al. [51] also reported significantly less correction of the lumbar curves than of the thoracic curves (38 compared to 50%, respectively). Lumbar curve magnitude or stiffness also correlates to decreased correction of the lumbar curve and lumbar curve decompensation [30, 52]. As a result of these and other studies, the pre-operative push-prone and supine lumbar radiographs were recommended as the best assessment of pre-operative flexibility imaging to predict the ideal amount of thoracic curve correction and expected spontaneous lumbar curve correction [53].

In contrast, several studies have shown spontaneous correction of the lumbar curve between 60 to 81%, which corresponded to the 61–83% correction of the thoracic curve [37, 54, 55]. They did not find a correlation between over correction of the thoracic curve and decreased spontaneous correction of the lumbar curve. One study states that newer intra-operative techniques using pedicle screws may have an enhanced capacity to control spontaneous correction of the lumbar spine which exceeds the pre-operative flexibility radiographic correction amount [37]. They have found up to 83% correction of the thoracic spine and 81% spontaneous correction of the lumbar spine when pre-operative flexibility imaging showed a spontaneous lumbar correction of 66%.

Thompson et al. [44] studied the influence of rod rotation for correction of the major curve on the secondary curve in computed tomography scans. They concluded that patients who underwent rod derotation techniques for selective fusion of the primary thoracic curve demonstrated decreased spontaneous correction of the secondary lumbar curve. This then led to a larger size of the secondary lumbar curve and later progression of this curve below their selective thoracic fusion. The rod derotation maneuver led to their reported 75% decompensation in King Type II curves. This is more common in those patients with larger and more deviated lumbar curves. However, Suk et al. [37] showed that the rod derotation maneuver did not lead decompensation.

Postoperative complications

Preservation of global coronal and sagittal balance is key to ensure good patient outcomes for all spinal deformity surgery, and coronal balance is at greater risk than sagittal balance in selective thoracic fusion. When the C7 plumb line is left of the curve pre-operatively, the coronal balance will increase to the left postoperatively since the spontaneous lumbar correction comes mostly from the proximal lumbar spine and not the distal lumbar spine [8].

Several studies examined the problem of postoperative coronal decompensation and found a prevalence of 4 to 41% [46, 51]. Poor outcomes are related with progression of the unfused lumbar curve below a selective fusion [42, 43], overcorrection of the thoracic curve [30, 44, 45], poor choice of fusion levels [42, 47, 56, 57], incorrect identification of curve patterns [30, 58], lumbar curve magnitude or stiffness [30, 52], and relative position and rotation of the apical vertebrae [30, 59]. In a study following patient outcomes with a minimum 5 years follow-up after selective thoracic fusion, the overall revision rate to accommodate worsening deformity was 6% (2/32 patients) [60]. In this study, 12 patients were considered marginal radiographic outcomes due to: 16% (5/32) with LIV more than 3 cm translation from the CSVL, 12.5% (4/32) with worsening lumbar AVT compared to pre-op, 3% (1/32) with worsening lumbar AVT compared to pre-op, 16% (5/32) with distal junctional kyphosis more than 10° increased from pre-op, and 6% (2/32) with lumbar Cobb angle more than 5° from pre-op. These results are consistent with previous reports in the literature [17, 36, 61].

Selective thoracolumbar/lumbar fusion

While the studies examining the selective fusion of thoracolumbar/lumbar curves are much fewer in number, it is no less feasible. The lack of literature on this topic may be due to the fact that extending a fusion from the lumbar spine to the thoracic spine does not lead to the same amount of motion loss as extending a fusion from the thoracic to the lumbar spine. Regardless, many of the same considerations as for selective thoracic fusion apply to selective thoracolumbar/lumbar fusions such as careful selection of fusion levels, correction amount, and potential complications. Lenke Type 5 and 6 curves are thoracolumbar/lumbar major curves with minor thoracic curves [13, 15, 16]. If the thoracic curve side bends to less than 25° and the T10–L2 kyphosis is less than 20°, it is classified as Lenke Type 5 curve and selective thoracolumbar/lumbar fusion is possible. However, even if the thoracic curve side bends to more than 25° and the T10–L2 kyphosis is more than 20° (Lenke Type 6), selective thoracolumbar/lumbar fusion is still possible if they meet the criteria.

In 2003, Sanders et al. [62] examined the criteria necessary for successful selective anterior fusion of thoracolumbar/lumbar curves. They followed 49 patients for 2 years after selective anterior thoracolumbar/lumbar fusion and determined that a thoracic curve of less than 40° was necessary for a satisfactory result. The best predictor of successful outcome was skeletal maturity as determined by the triradiate cartilage. Also predictive of a satisfactory outcome was thoracolumbar/lumbar to thoracic Cobb ratio of greater than 1.25, thoracolumbar/lumbar curve 55° or less, and/or a thoracic curve side-bending Cobb measurement of 20° or less. These factors for good outcomes after selective fusion of thoracolumbar/lumbar curves are shown in Table 2. Similar to the recommendations listed in

Table 2 Factors for selective fusion of thoracolumbar/lumbar curves

Category	Criteria	Notes
Candidates	Lenke 5C, 6C	
Clinical parameters	Lifestyle and activity level	
	Lumbar rotational prominence > thoracic prominence	
	Soft tissue flexibility: thumb abduction test	
Radiographic parameters		
Coronal plane ratio criteria	$\frac{\text{AVT thoracolumbar/lumbar}}{\text{AVTthoracic}} > 1.25$	Possible if AVT criteria only
	$\frac{\text{AVR thoracolumbar/lumbar}}{\text{AVRthoracic}} > 1.25$	Better if 2 or 3 criteria met
	$\frac{\text{Thoracolumbar/lumbar Cobb angle}}{\text{ThoracicCobbangle}} > 1.25$	
Sagittal plane criteria	Thoracolumbar (T10–L2) kyphosis < 10°	If UIV between T10 and L2
Skeletal maturity	Triradiate cartilage—closed	
Additional criteria	Thoracic side bender < 25°	Possible if >25° if more criteria met
	Thoracic curve < 40°	Possible if >40° if T10–L2 >20° if UIV ≥T10

AVT apical vertebral translation, *AVR* apical vertebral rotation, *UIV* uppermost instrumented vertebra, *TL/L* thoracolumbar/lumbar

Fig. 2 Selective thoracic fusion for Lenke 1CN curve

Fig. 3 Selective thoracolumbar fusion for Lenke 6C curve

Table 1, the studies for Table 2 are level 4 evidence based on case series reports.

Schulte et al. [27] in 2006 studied the spontaneous vertebral derotation of secondary curves. They found a significant spontaneous derotation of lumbar curves after selective anterior thoracic fusion. Yet for selective anterior thoracolumbar/lumbar fusion, there was an increase in the rotation of the compensatory thoracic curve. A spontaneous thoracic correction of 36% was shown in this study. Li et al. [63] followed patients after selective lumbar fusion in Lenke 5C curves. They found an average of 57% lumbar curve correction and 26% thoracic curve correction with a minimum 2 year follow-up.

Conclusion

Selective fusion of thoracic or thoracolumbar/lumbar curves in C lumbar modifiers is a way to provide balanced curve correction while leaving the maximum number of mobile vertebral segments. The majority of studies demonstrated satisfactory outcomes based upon patient activity level, curve character such as curve magnitude, flexibility, rotation, translation and sagittal profile, and skeletal maturity. Poor patient selection, selection of the incorrect fusion levels, and inadequate correction can lead to progressive deformity, adding-on, shoulder imbalance, and worsening trunk rotation. Most of the literature on this subject comes from level 4 studies that are case series and higher level comparison studies would be beneficial to decision making. Further research is needed to evaluate the long-term outcomes of selective anterior or posterior instrumentation methods.

Conflict of interest None.

Appendix: Case presentation

Case 1

N.P. is a 17-year-old female with idiopathic scoliosis. Preoperative standing AP radiograph showed a right thoracic curve of 56° and a left thoracolumbar curve of 52° that bent down to 4° on side-bending films. The thoracic apical vertebral rotation was 2 and the lumbar apical vertebral rotation was 2. The thoracic apical vertebral translation was 37 mm and the lumbar apical vertebral translation was 32 mm. Pre-operative standing lateral radiograph showed thoracic kyphosis at T5–T12 7° and lumbar lordosis T12–S1 at 80°. Scoliometer measurement showed a thoracic angle of 14° and lumbar angle of 5°. She also has an L5/S1 grade 2 spondylolisthesis. She underwent selective thoracic fusion from T4–T11 and postoperative thoracic curve of 35° and lumbar curve of 29° (Fig. 2).

Case 2

T.F. is a 13-year-old boy with an idiopathic scoliosis. Pre-operative standing AP radiograph showed a right thoracic curve of 47° and a left thoracolumbar curve of 80°. The lumbar apical vertebral rotation at T13 was 40° and thoracic apical vertebral rotation at T7 was 5°, according to Perdriolle. The thoracic apical vertebral translation was 18 mm and the lumbar apical vertebral translation was 77 mm. The C7 plumb line was 44 mm toward the left side. Pre-operative standing lateral radiograph showed thoracic kyphosis at T5–T12 of 3°, thoracolumbar kyphosis at T10–L2 of 23°, and lumbar lordosis at T12–S1 of 42°. The left side bender of the thoracolumbar curve was 58° and the right side bender was 22°. He also had a left-side only synostosis of L5–S1. His curve is a 6C according to the Lenke classification system. He underwent posterior osteotomy at L5–S1 and selective posterior thoracolumbar instrumentation and fusion at T10–L3 and presented at 12 months follow-up with satisfactory frontal and sagittal spinal alignment (Fig. 3).

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