

# Spinal Sagittal Alignment Changes During Childhood

## Results of a National Cohort Analysis of 1,059 Healthy Children

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**Background:** In the past decades, it has been recognized that sagittal alignment of the spine is crucial. Although the evolution of spinal alignment with growth has previously been described, there are no data for key parameters such as the exact shapes (extent and magnitude) of spinal curvatures. The goals of this study were therefore to determine normative values of spinopelvic sagittal parameters and to explore their variation during growth, based on the analysis of a large national cohort of healthy children.

**Methods:** The radiographic data of 1,059 healthy children were analyzed in a retrospective, multicenter study. Full spine radiographs were used to measure several sagittal parameters, such as pelvic parameters, T1-T12 thoracic kyphosis (TK), and L1-S1 lumbar lordosis (LL). TK was divided into proximal, middle, and distal parts, and LL was divided into proximal and distal parts. Patients were stratified into 5 groups according to skeletal maturity (based on age, Risser stage, and triradiate cartilage status).

**Results:** During growth, pelvic incidence increased from 40° to 46° and pelvic tilt increased from 4° to 9° ( $p < 0.05$ ), whereas sacral slope remained constant. The peak of change in pelvic parameters occurred at the beginning of pubertal growth in Group 2 (the first part of the pubertal growth spurt). TK slightly increased among groups from 39° to 41° ( $p = 0.005$ ), with the peak of change occurring in Group 4 (pubertal growth deceleration). LL increased from 51° to 56° ( $p < 0.001$ ), with the peak of change occurring in Group 3 (the second part of the pubertal growth spurt). Segmental analysis revealed that most of the TK and LL changes occurred in the distal TK and proximal LL, with the other parts remaining constant.

**Conclusions:** This is one of the largest studies showing changes in sagittal alignment with growth in normal children and adolescents. We found that changes in spinal shape were cascading phenomena. At the beginning of the growth peak, pelvic incidence increased. This change in pelvic morphology led to an increase in LL, involving its proximal part. Finally, TK increased, in its distal part, at the end of pubertal growth.

**Level of Evidence:** Prognostic Level IV. See Instructions for Authors for a complete description of levels of evidence.

The human spine is composed of 3 main sagittal curvatures: cervical lordosis, thoracic kyphosis (TK), and lumbar lordosis (LL)<sup>1</sup>. Since the 1990s, it has been widely demonstrated that spinal sagittal alignment is intimately associated with pelvic morphology and orientation. Indeed, the sacrum can be considered as a pedestal for the spine, determining the shape and magnitude of the overlying sagittal curvatures<sup>2-4</sup>. As LL has been proven to change according to pelvic parameters, sagittal curvatures can be determined according to the slope-to-slope concept: large LL is associated with large TK and cervical lordosis. Although this relationship seems relatively simple, large variability in normal sagittal alignment exists in healthy subjects. Moreover, mature biped-

alism is progressively acquired during childhood, leading to dynamic postural changes throughout growth, with subsequent sagittal spinal curvature adaptations<sup>5-7</sup>. There is a paucity of data on normal pelvic growth. Mac-Thiong et al. compared 2 groups of patients (1 group that was 3 to 10 years of age and 1 group that was >10 to <18 years of age) and reported an increase in the mean pelvic incidence (PI) (from 44° to 47°) and the mean pelvic tilt (PT) (from 6° to 8°)<sup>8</sup>. Interestingly, they found no difference between boys and girls. In the frontal plane, pelvic height and width seem to increase until the age of 14 years<sup>9</sup>. The growth of the pelvis will change pelvic morphology and potentially will have an influence on spinal shape.

**Disclosure:** The **Disclosure of Potential Conflicts of Interest** forms are provided with the online version of the article (<http://links.lww.com/JBJS/H461>).

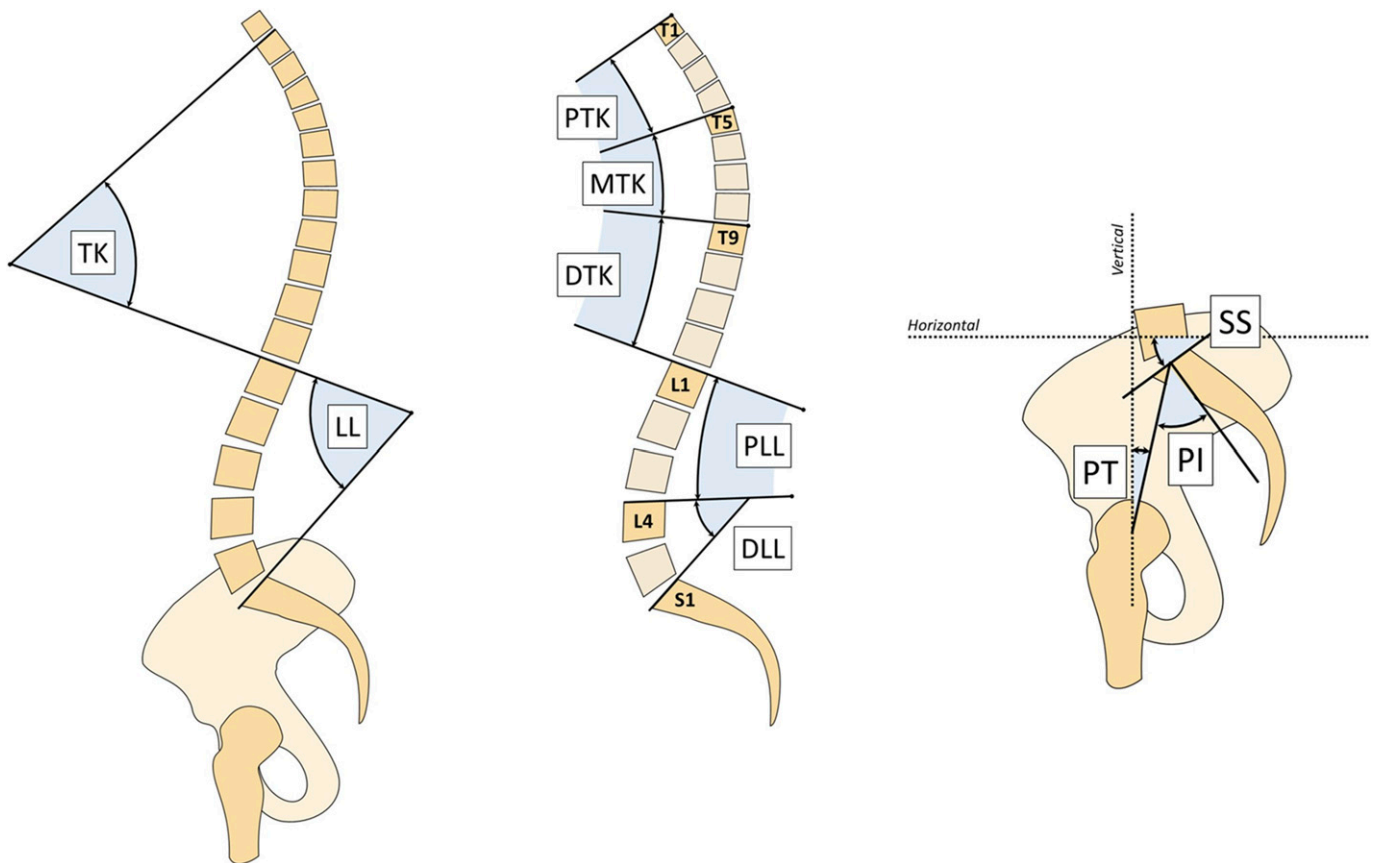


Fig. 1  
Radiographic parameters. TK = thoracic kyphosis, LL = lumbar lordosis, PTK = proximal TK, MTK = middle TK, DTK = distal TK, PLL = proximal LL, DLL = distal LL, SS = sacral slope, PT = pelvic tilt, and PI = pelvic incidence.

During the last 3 decades, analysis of sagittal curvature in pathologic conditions has become a hot topic in the spine community, as sagittal malalignment has been associated with poorer quality-of-life scores in adults and a higher risk of mechanical complications<sup>10,11</sup>. In children and adolescents, the sagittal balance is equally important because optimal alignment in scoliosis surgery will decrease the risk of junctional mechanical failure and altered quality of life in the long term<sup>12-14</sup>. Therefore, to have a better basic knowledge of pediatric spine issues, we need to understand more clearly how spinal curvatures change.

The current literature remains scarce with regard to the physiological sagittal alignment in children<sup>15,16</sup>. Based on segmental analysis, Cil et al. demonstrated only slight changes in LL and TK during growth<sup>15</sup>. In 2011, Mac-Thiong et al. reported consistent results, with higher values of sagittal curvatures in adolescents >10 to <18 years of age compared with children 3 to 10 years of age<sup>8</sup>. These analyses were based on limited cohorts and did not account for key parameters such as precise biomechanical analysis of spinal curvatures (extent and magnitude). In addition, only few data exist on younger children, especially before adolescence.

As PI increases during growth<sup>17</sup>, we hypothesized that spinopelvic alignment might vary with age in children and

adolescents. Nevertheless, there is still a lack of normal reference values at different growth stages that could be used when treating patients with early-onset or adolescent idiopathic scoliosis.

The goals of this study were therefore to determine normative values of spinopelvic sagittal parameters and to explore their variation during growth, based on the analysis of a large national cohort of healthy children.

## Materials and Methods

### Study Design and Subject Selection

This is a retrospective, cross-sectional, multicenter study. Six pediatric spine centers were involved in the study. From September 2019 to March 2020, picture archiving and communication systems were queried for spinal radiographs of asymptomatic children. Inclusion criteria were an age of <19 years at the time of the evaluation, absence of spinal or lower-limb pathology, and no contraindication for radiation exposure. Subjects with spinal deformity (scoliosis with a Cobb angle of >10°, Scheuermann kyphosis, spondylolisthesis) and major lower-limb discrepancy (>10 mm) were excluded from the study. Radiographs were made mainly for scoliosis screening in patients with a family history of spinal deformity. Following

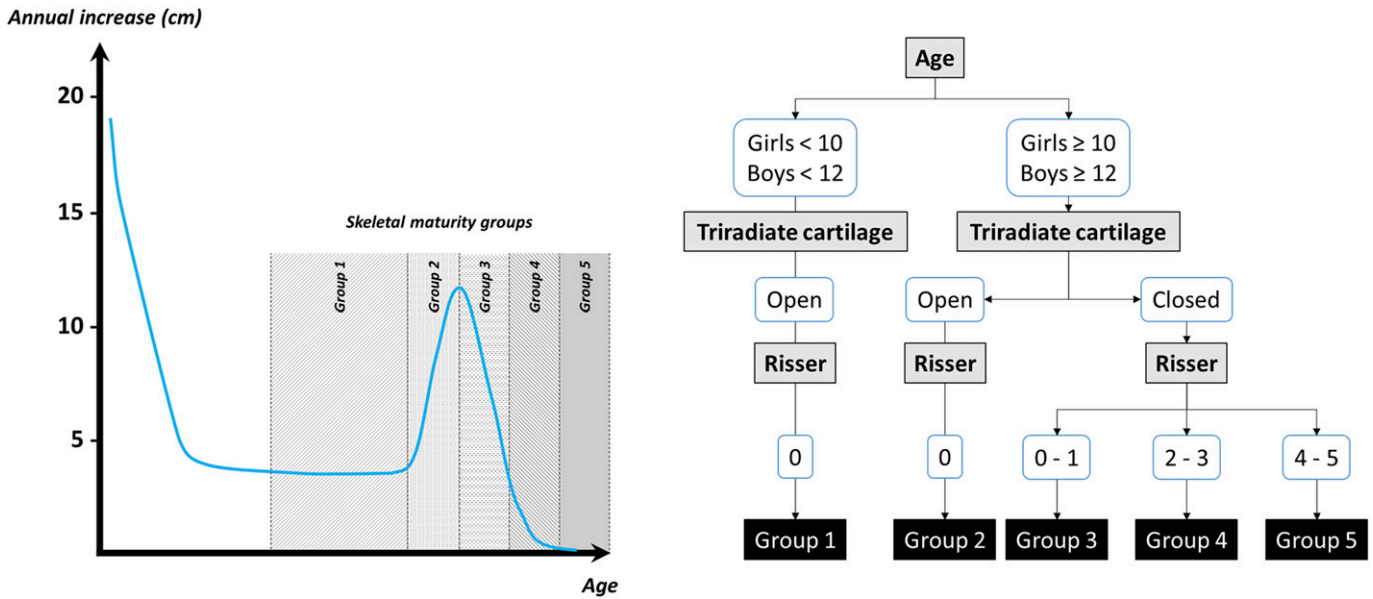


Fig. 2 Patient stratification according to growth stage.

institutional review board approval (FC/2019-91), 1,059 healthy children were enrolled after informed written consent of the patients and their parents or legal guardians.

**Radiographic Analysis**

All patients underwent biplanar, standing, full-length spinal radiographs (EOS Imaging). In order to be included in the

| TABLE I Results of ANOVA Comparing Radiographic Parameters According to Skeletal Maturity |                               |                               |                               |                               |                               |                  |
|---|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|------------------|
| Parameter   | Group 1*<br>(N = 146)         | Group 2*<br>(N = 203)         | Group 3*<br>(N = 166)         | Group 4*<br>(N = 143)         | Group 5*<br>(N = 401)         | ANOVA<br>P Value |
| Age (yr)  | 8.7 ± 1.8                     | 12 ± 1.4                      | 13 ± 1.4                      | 14.5 ± 1.3                    | 16.1 ± 1.7                    | <0.001           |
| PI (deg)  | 40.4 ± 9.1<br>(38.9 to 41.8)  | 43.7 ± 10.5<br>(42.2 to 45.1) | 44.7 ± 11.9<br>(42.9 to 46.5) | 44.7 ± 10.5<br>(43 to 46.5)   | 45.8 ± 11.9<br>(44.7 to 47)   | <0.001           |
| SS (deg)  | 36.2 ± 7.5<br>(35 to 37.4)    | 38.8 ± 7.8<br>(37.7 to 39.9)  | 37.8 ± 9<br>(36.4 to 39.2)    | 37.8 ± 9.2<br>(36.3 to 39.3)  | 37.3 ± 9.2<br>(36.4 to 38.2)  | 0.079            |
| PT (deg)  | 4.2 ± 7.2<br>(3 to 5.3)       | 4.8 ± 8.1<br>(3.7 to 5.9)     | 7 ± 9<br>(5.6 to 8.3)         | 7 ± 8<br>(5.6 to 8.3)         | 8.5 ± 8<br>(7.7 to 9.3)       | <0.001           |
| TK (deg)  | 38.8 ± 12.4<br>(36.8 to 40.8) | 37.2 ± 12.1<br>(35.5 to 38.9) | 37.2 ± 13.1<br>(35.1 to 39.2) | 39.5 ± 12<br>(37.6 to 41.5)   | 40.6 ± 12.2<br>(39.4 to 41.8) | 0.005            |
| LL (deg)  | 50.5 ± 11.2<br>(48.6 to 52.3) | 54.3 ± 11<br>(52.7 to 55.8)   | 53.7 ± 12.3<br>(51.8 to 55.6) | 55.8 ± 11.5<br>(53.9 to 57.7) | 55.6 ± 11.7<br>(54.5 to 56.8) | <0.001           |
| T1-T5 proximal TK (deg)   | 10.0 ± 9.4<br>(8.5 to 11.5)   | 8.0 ± 8.3<br>(6.9 to 9.2)     | 7.9 ± 8.6<br>(6.6 to 9.2)     | 7.6 ± 8.2<br>(6.2 to 8.9)     | 8.7 ± 8.8<br>(7.9 to 9.6)     | 0.106            |
| T5-T9 middle TK (deg)   | 21.0 ± 7.8<br>(19.7 to 22.3)  | 21.2 ± 6.6<br>(20.3 to 22.2)  | 21.2 ± 7.3<br>(20.1 to 22.4)  | 21.3 ± 7.8<br>(20 to 22.6)    | 21.3 ± 7.4<br>(20.5 to 22)    | 0.998            |
| T9-L1 distal TK (deg)   | 7.0 ± 7.3<br>(5.8 to 8.2)     | 6.9 ± 7.7<br>(5.8 to 8)       | 6.9 ± 8.6<br>(5.5 to 8.2)     | 9.9 ± 7.8<br>(8.6 to 11.2)    | 9.4 ± 8.7<br>(8.6 to 10.3)    | <0.001           |
| L1-L4 proximal LL (deg)   | 14.7 ± 9.5<br>(13.1 to 16.3)  | 16.6 ± 9.2<br>(15.3 to 17.8)  | 16.6 ± 9.4<br>(15.1 to 18)    | 17.8 ± 9.6<br>(16.2 to 19.4)  | 19.7 ± 9.6<br>(18.8 to 20.7)  | <0.001           |
| L4-S1 distal LL (deg)   | 35.8 ± 8.0<br>(34.5 to 37.1)  | 37.7 ± 8.3<br>(36.6 to 38.9)  | 37.1 ± 8.7<br>(35.8 to 38.5)  | 38.1 ± 8.8<br>(36.6 to 39.5)  | 35.9 ± 8.6<br>(35.1 to 36.8)  | 0.018            |

\*The values are given as the mean and the standard deviation, with or without the 95% confidence interval in parentheses.

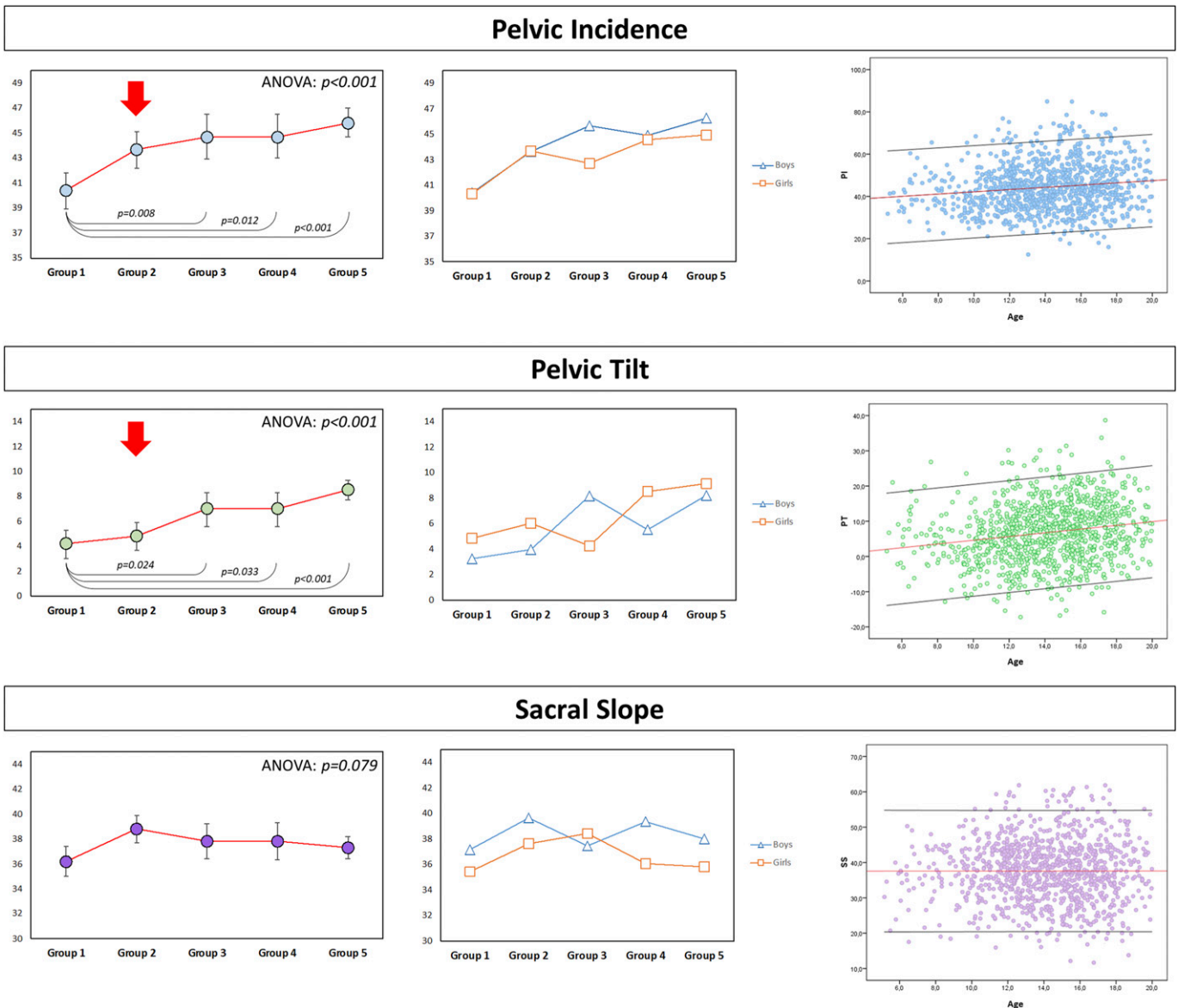


Fig. 3

Evolution of pelvic parameters among groups. The left column shows the results of ANOVA with a Bonferroni correction; the graphed values are the mean and 95% confidence interval (CI), and the red arrows indicate the peak of change. The center column shows the differences between boys and girls. The right column shows scatterplots of the parameters versus age; the red line shows the results of linear regression analysis, and the black lines show the 95% CI.

study, radiographs had to include the femoral heads, the base of the skull, and the entire cervical spine. Patients were asked to stand in a comfortable position, with hips and knees in full extension and their fists on their clavicles or jaws<sup>18</sup>. All lateral radiographs were reconstructed by a senior spine surgeon using a semiautomated method, by graphical identification of anatomical landmarks (vertebral end plates and femoral heads) (KEOPS software; SMAIO). Each radiograph was measured by 1 of the authors of the study and was double-checked by another author; both observers were blinded to patient age. The following sagittal parameters were collected: T1-T12 TK, L1-S1 LL, PI, sacral slope (SS), and PT. According to Lafage

et al.<sup>19</sup>, TK was divided into proximal (sagittal angle between the upper end plates of T1 and T5), middle (the same angle for T5-T9, the apex of kyphosis), and distal parts (the same angle for T9-L1). LL was divided into a proximal part (sagittal angle between the upper end plates of L1 and L4) and a distal part (the same angle for L4-S1) (Fig. 1).

Chronological age and the skeletal maturity markers visible on full spine radiographs, namely the triradiate cartilage and the Risser sign, were assessed. Subjects were then divided into 5 subgroups according to their growth stage (Fig. 2): Group 1 (prepuberty) included girls <10 years of age and boys <12 years of age with open triradiate cartilage and Risser 0.

**TABLE II Significance of Pairwise Differences in Radiographic Parameters Between Groups\***

| Parameter          | P Value |         |         |         |
|--------------------|---------|---------|---------|---------|
|                    | Group 1 | Group 2 | Group 3 | Group 4 |
| <b>PI</b>          |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | 0.008   | NS      | —       | —       |
| Group 4            | 0.012   | NS      | NS      | —       |
| Group 5            | <0.001  | NS      | NS      | NS      |
| <b>PT</b>          |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | 0.024   | NS      | —       | —       |
| Group 4            | 0.033   | NS      | NS      | —       |
| Group 5            | <0.001  | <0.001  | NS      | NS      |
| <b>TK</b>          |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | NS      | NS      | —       | —       |
| Group 4            | NS      | NS      | NS      | —       |
| Group 5            | NS      | 0.023   | 0.041   | NS      |
| <b>Distal TK</b>   |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | NS      | NS      | —       | —       |
| Group 4            | 0.024   | 0.007   | 0.011   | —       |
| Group 5            | 0.020   | 0.003   | 0.007   | NS      |
| <b>LL</b>          |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | 0.042   | —       | —       | —       |
| Group 3            | NS      | NS      | —       | —       |
| Group 4            | 0.001   | NS      | NS      | —       |
| Group 5            | <0.001  | NS      | NS      | NS      |
| <b>Proximal LL</b> |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | NS      | NS      | —       | —       |
| Group 4            | NS      | NS      | NS      | —       |
| Group 5            | <0.001  | 0.001   | 0.003   | NS      |
| <b>Distal LL</b>   |         |         |         |         |
| Group 1            | —       | —       | —       | —       |
| Group 2            | NS      | —       | —       | —       |
| Group 3            | NS      | NS      | —       | —       |
| Group 4            | NS      | NS      | NS      | —       |
| Group 5            | NS      | NS      | NS      | NS      |

\*Post hoc testing. NS = not significant.

Group 2 (first part of pubertal growth spurt) included girls  $\geq 10$  years of age and boys  $\geq 12$  years of age with open triradiate cartilage and Risser 0. Group 3 (second part of pubertal growth

spurt) included girls and boys with closed triradiate cartilage and Risser 0 or 1. Group 4 (pubertal growth deceleration) included girls and boys with closed triradiate cartilage and Risser 2 or 3. Group 5 (end of puberty) included girls and boys with closed triradiate cartilage and Risser 4 or 5.

### Statistical Analysis

Data are presented as the mean and the standard deviation. Normality of distributions was tested before analysis using Kolmogorov-Smirnov tests. Differences between groups were assessed using analysis of variance (ANOVA). Post hoc analyses were performed using a Bonferroni correction. The comparison between boys and girls in each growth group was performed using Student t tests. Analyses of differences between skeletally immature and mature subjects were undertaken according to triradiate cartilage status (open group or closed group) using Student t tests. Differences were considered as significant when  $p < 0.05$ . All statistical tests were performed using SPSS version 20 (IBM).

### Source of Funding

No funding was received for this study.

### Results

#### Study Population

A total of 1,059 subjects were included. The mean age was  $13.6 \pm 3.0$  years (range, 5 to 18 years), with 643 girls and 416 boys (sex ratio: 1.5:1). After stratification by growth stage, there were 146 subjects in Group 1, 203 in Group 2, 166 in Group 3, 143 in Group 4, and 401 in Group 5 (Table I).

#### Parameter Changes According to Growth Stage

During growth, PI increased from  $40^\circ$  to  $46^\circ$  and PT increased from  $4^\circ$  to  $9^\circ$ . However, SS remained constant during the entire growth period ( $p = 0.079$ ) (Table I). Post hoc analysis revealed that most changes in PI and PT occurred between Groups 1 and 3 (ages  $\geq 10$  years for girls or  $\geq 12$  years for boys, Risser 0, open triradiate cartilage) (Fig. 3, Table II).

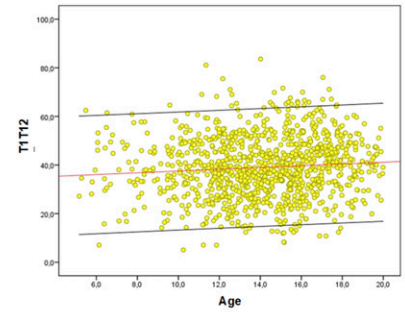
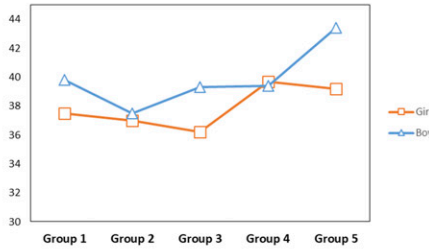
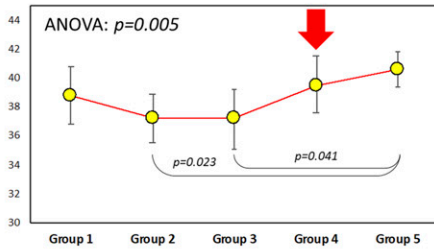
With regard to sagittal spinal curves, TK slightly increased among groups from  $39^\circ$  to  $41^\circ$  ( $p = 0.005$ ). The main TK change was observed in Group 4 compared with Group 1. During growth, proximal TK ( $p = 0.106$ ) and middle TK ( $p = 0.998$ ) remained constant, whereas distal TK increased ( $p < 0.001$ ), with the peak of change occurring in Group 4 (Fig. 4, Table II). There were also increases in LL (from  $51^\circ$  to  $56^\circ$ ;  $p < 0.001$ ) and proximal LL (from  $15^\circ$  to  $20^\circ$ ;  $p < 0.001$ ), with the peak of change occurring between Groups 2 and 4 for LL (Fig. 5, Table II).

The comparison between boys and girls found few significant differences, such as for PT, which was higher in boys than in girls across the groups. Furthermore, L1-S1 and L4-S1 LL were significantly higher in girls than in boys (Table III).

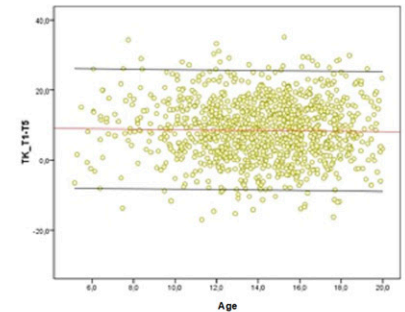
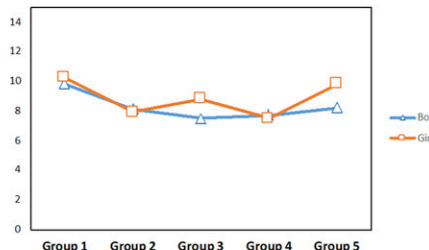
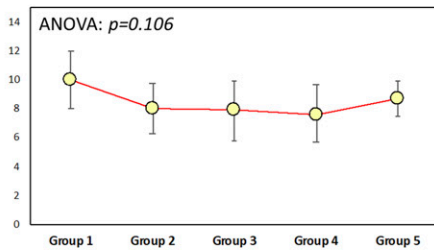
#### Stratification According to Triradiate Cartilage Status

The open group included 349 subjects (mean age,  $10.6 \pm 2.2$  years), and the closed group included 710 subjects (mean age,  $15 \pm 2.0$  years). PI was significantly higher ( $p < 0.001$ ) in the

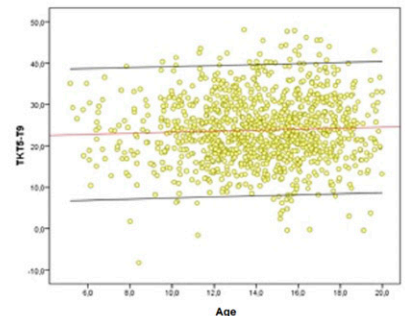
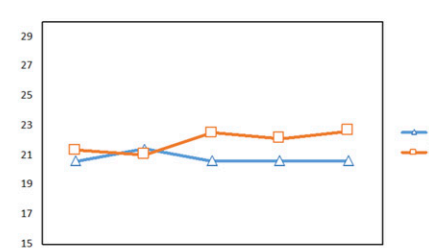
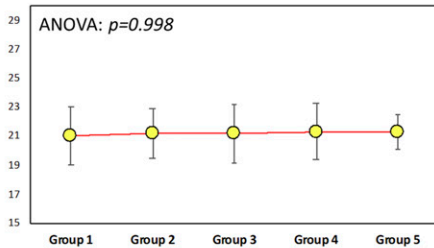
## Thoracic Kyphosis (T1T12)



## PTK (T1T5)



## MTK (T5T9)



## DTK (T9T12)

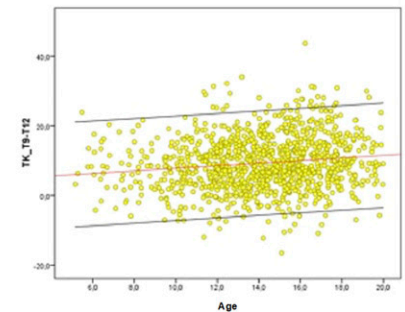
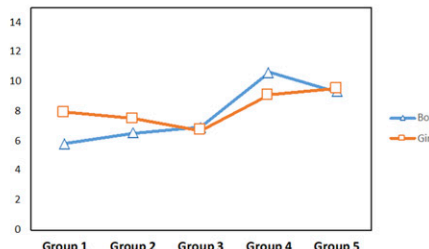
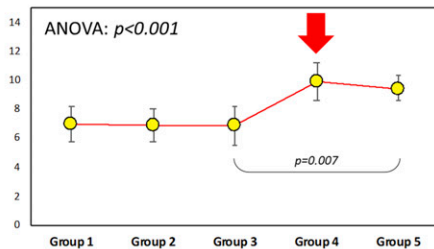
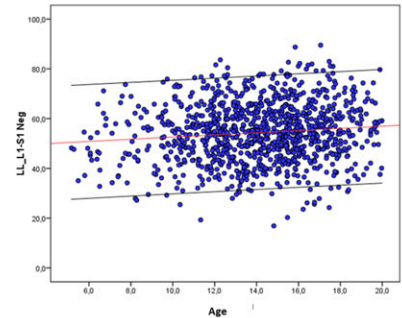
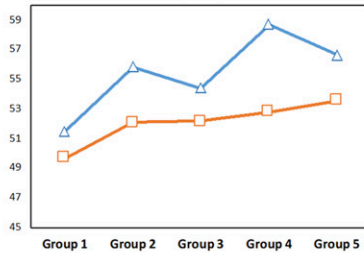
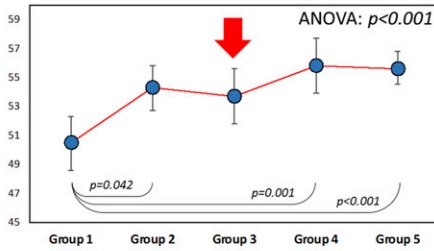


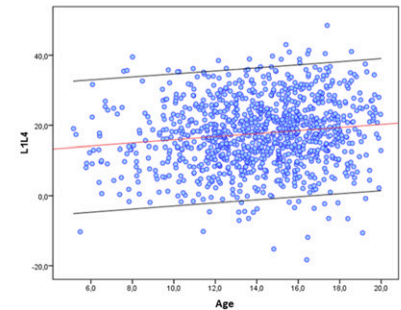
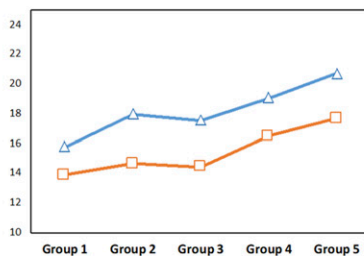
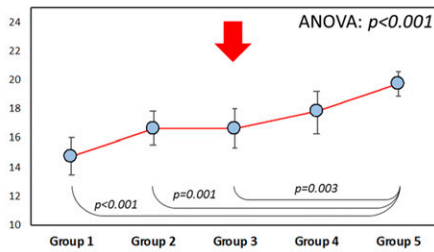
Fig. 4

Evolution of TK among groups. The left column shows the results of ANOVA with a Bonferroni correction; the graphed values are the mean and 95% confidence interval (CI), and the red arrows indicate the peak of change. The center column shows the differences between boys and girls. The right column shows scatterplots of the parameter versus age; the red line shows the results of linear regression analysis, and the black lines show the 95% CI. PTK = proximal TK, MTK = middle TK, and DTK = distal TK.

## Lumbar Lordosis (L1S1)



## PLL (L1L4)



## DLL (L4S1)

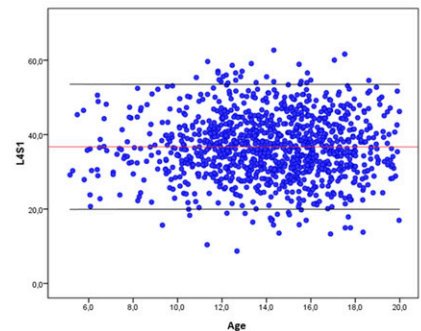
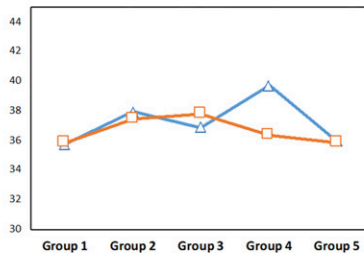
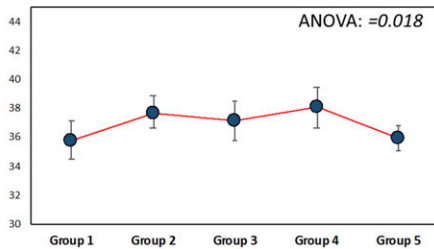


Fig. 5

Evolution of LL among groups. The left column shows the results of ANOVA with a Bonferroni correction; the graphed values are the mean and 95% confidence interval (CI), and the red arrows indicate the peak of change. The center column shows differences between boys and girls. The right column shows scatterplots of the parameter versus age; the red line shows the results of linear regression analysis, and the black lines show the 95% CI. PLL = proximal LL, and DLL = distal LL.

closed group ( $45.4^\circ$ ) compared with the open group ( $42.3^\circ$ ), and PT was also significantly higher ( $p < 0.001$ ) in the closed group ( $7.8^\circ$ ) compared with the open group ( $4.6^\circ$ ). SS remained similar ( $p = 0.721$ ) between groups:  $37.7^\circ$  compared with  $37.5^\circ$  (Table IV). TK was significantly higher ( $p = 0.036$ ) in the closed group ( $39.6^\circ$ ) than in the open group ( $37.9^\circ$ ). This difference was due to the difference in distal TK ( $8.9^\circ$  in the closed group compared with  $6.9^\circ$  in the open group;  $p < 0.001$ ), whereas proximal TK ( $8.8^\circ$  compared with  $8.3^\circ$ ;  $p = 0.352$ ) and middle TK ( $21.1^\circ$  compared with  $21.3^\circ$ ;  $p = 0.813$ ) were not significantly different. LL was significantly

higher ( $p = 0.001$ ) in the closed group ( $55.2^\circ$ ) compared with the open group ( $52.7^\circ$ ). The difference in LL was due to the difference in proximal LL:  $15.8^\circ$  compared with  $18.6^\circ$  ( $p < 0.001$ ). Distal LL was not significantly different between groups:  $36.9^\circ$  in the open group compared with  $36.6^\circ$  in the closed group ( $p = 0.640$ ).

## Discussion

This is one of the largest series describing the normative values of sagittal alignment parameters in children. Although physiologic alignment has already been studied in previous

TABLE III Comparison of Sagittal Parameters Between Boys and Girls According to Skeletal Maturity

| Parameter         | Group 1         |                |         | Group 2          |                |         |
|-------------------|-----------------|----------------|---------|------------------|----------------|---------|
|                   | Girls* (N = 63) | Boys* (N = 83) | P Value | Girls* (N = 119) | Boys* (N = 84) | P Value |
| Age (yr)          | 7.7 ± 1.3       | 9.5 ± 1.6      | <0.001  | 11.2 ± 1.1       | 13.0 ± 1.1     | <0.001  |
| PI (deg)          | 40.4 ± 9.1      | 40.3 ± 9.1     | 0.953   | 43.6 ± 10.7      | 43.7 ± 10.3    | 0.967   |
| SS (deg)          | 37.2 ± 6.5      | 35.5 ± 8.2     | 0.176   | 39.7 ± 8.1       | 37.6 ± 7.2     | 0.071   |
| PT (deg)          | 3.3 ± 8         | 4.9 ± 6.4      | 0.179   | 4 ± 8.3          | 6 ± 7.6        | 0.072   |
| TK (deg)          | 37.5 ± 12.1     | 39.8 ± 12.6    | 0.275   | 37 ± 12.5        | 37.5 ± 11.5    | 0.771   |
| LL (deg)          | 51.5 ± 10.6     | 49.7 ± 11.6    | 0.339   | 55.8 ± 11        | 52.1 ± 10.6    | 0.017   |
| Proximal TK (deg) | 9.8 ± 9         | 10.2 ± 9.8     | 0.83    | 8.1 ± 8.1        | 7.9 ± 8.5      | 0.921   |
| Middle TK (deg)   | 20.6 ± 6.9      | 21.3 ± 8.5     | 0.582   | 21.4 ± 6.6       | 21 ± 6.6       | 0.912   |
| Distal TK (deg)   | 5.8 ± 7.4       | 7.9 ± 7.1      | 0.079   | 6.5 ± 7.8        | 7.5 ± 7.7      | 0.369   |
| Proximal LL (deg) | 15.8 ± 10       | 13.9 ± 9.2     | 0.233   | 17.9 ± 9.3       | 14.6 ± 8.6     | 0.011   |
| Distal LL (deg)   | 35.7 ± 8.4      | 35.8 ± 7.7     | 0.928   | 37.9 ± 8.6       | 37.5 ± 7.9     | 0.715   |

\*The values are given as the mean and the standard deviation.

TABLE III (continued)

| Group 3          |                |         | Group 4         |                |         | Group 5          |                 |         |
|------------------|----------------|---------|-----------------|----------------|---------|------------------|-----------------|---------|
| Girls* (N = 114) | Boys* (N = 52) | P Value | Girls* (N = 74) | Boys* (N = 69) | P Value | Girls* (N = 273) | Boys* (N = 128) | P Value |
| 12.6 ± 1.3       | 13.8 ± 1.4     | <0.001  | 14.1 ± 1.4      | 14.9 ± 1.1     | 0.001   | 15.8 ± 1.8       | 16.7 ± 1.2      | <0.001  |
| 45.6 ± 12.2      | 42.7 ± 10.9    | 0.138   | 44.9 ± 11.3     | 44.6 ± 9.6     | 0.848   | 46.2 ± 12.1      | 45 ± 11.4       | 0.312   |
| 37.5 ± 9.4       | 38.4 ± 8.2     | 0.527   | 39.4 ± 8.8      | 36.1 ± 9.4     | 0.031   | 38 ± 9.3         | 35.8 ± 9        | 0.025   |
| 8.2 ± 8.5        | 4.3 ± 9.5      | 0.009   | 5.5 ± 7.2       | 8.5 ± 8.5      | 0.026   | 8.2 ± 8.4        | 9.2 ± 7.2       | 0.286   |
| 36.2 ± 12.5      | 39.3 ± 14.2    | 0.149   | 39.7 ± 12.5     | 39.4 ± 11.6    | 0.886   | 39.2 ± 11.8      | 43.4 ± 12.6     | 0.001   |
| 54.4 ± 12.6      | 52.2 ± 11.6    | 0.283   | 58.7 ± 10.6     | 52.8 ± 11.7    | 0.002   | 56.6 ± 11.5      | 53.5 ± 12       | 0.014   |
| 7.5 ± 8.2        | 8.8 ± 9.5      | 0.392   | 7.7 ± 7.9       | 7.5 ± 8.4      | 0.854   | 8.2 ± 8.4        | 9.9 ± 9.5       | 0.08    |
| 20.6 ± 7.2       | 22.5 ± 7.5     | 0.132   | 20.6 ± 7.1      | 22.1 ± 8.4     | 0.24    | 20.6 ± 7.1       | 22.7 ± 7.9      | 0.01    |
| 6.9 ± 8.9        | 6.7 ± 7.9      | 0.852   | 10.6 ± 7.8      | 9.1 ± 7.7      | 0.25    | 9.3 ± 8.3        | 9.6 ± 9.5       | 0.743   |
| 17.5 ± 9.1       | 14.4 ± 9.9     | 0.046   | 19 ± 9.7        | 16.5 ± 9.4     | 0.112   | 20.7 ± 9.9       | 17.7 ± 8.8      | 0.003   |
| 36.8 ± 9.2       | 37.8 ± 7.6     | 0.524   | 39.7 ± 8.4      | 36.3 ± 8.9     | 0.023   | 35.9 ± 8.9       | 35.9 ± 8        | 0.926   |

cohorts<sup>8,15,16</sup>, the originality of our analysis involves the group definitions. We thought that stratifying the population on the basis of an age criterion was not relevant because skeletal maturity has a large variability for a given age, depending on sex and puberty onset. Instead, parameters allowing subjects to be situated relative to their pubertal growth peak and skeletal maturity were preferred. Therefore, a combination of age, triradiate cartilage status, and Risser sign was used.

Several interesting changes during growth in sagittal alignment were found. First, our results suggested that the first anatomical structure to change was the pelvis, with most of the changes occurring at the beginning of the pubertal growth peak (ages of ≥10 years for girls and ≥12 years for boys, Risser 0, open triradiate cartilage). PI slightly increased with

skeletal maturation, from 40° to 46° at the end of growth, which is consistent with previous literature. However, the fact that PT increased without any change in SS had rarely been emphasized. By definition, pelvic parameters are linked to each other according to the formula  $PI = PT + SS^{20}$ . Therefore, a change in PT should result in a reciprocal change in SS. The fact that PT increased along with PI and independent of SS probably reflects the anterior-posterior growth of the pelvis, which results in posterior migration of the sacral end plate with regard to the femoral heads. However, SS remained constant, meaning that anterior-posterior growth of the pelvis did not provoke any change in sacral orientation in the pelvic ring. Nevertheless, this theory is hypothetical and remains to be proven with further research.

Secondary to pelvic parameter changes, LL was found to increase during the second half of the pubertal growth peak,

TABLE IV Comparison of Spinopelvic Parameters Between Groups According to Triradiate Cartilage Status

| Parameter               | Open Group* (N = 349)      | Closed Group* (N = 710)    | P Value |
|-------------------------|----------------------------|----------------------------|---------|
| Age (yr)                | 10.6 ± 2.2                 | 15 ± 2                     | <0.001  |
| PI (deg)                | 42.3 ± 10.1 (41.2 to 43.4) | 45.4 ± 11.6 (44.5 to 46.2) | <0.001  |
| SS (deg)                | 37.7 ± 7.8 (36.9 to 38.5)  | 37.5 ± 9.2 (36.8 to 38.2)  | 0.721   |
| PT (deg)                | 4.6 ± 7.7 (3.8 to 5.4)     | 7.8 ± 8.3 (7.2 to 8.5)     | <0.001  |
| T1-T12 TK (deg)         | 37.9 ± 12.2 (36.6 to 39.1) | 39.6 ± 12.5 (38.6 to 40.5) | 0.036   |
| T1-T5 proximal TK (deg) | 8.8 ± 8.8 (7.9 to 9.7)     | 8.3 ± 8.6 (7.7 to 9)       | 0.352   |
| T5-T9 middle TK (deg)   | 23.5 ± 7.7 (22.7 to 24.3)  | 24.0 ± 7.9 (23.4 to 24.6)  | 0.813   |
| T9-T12 distal TK (deg)  | 7.9 ± 6.9 (7.1 to 8.6)     | 10.0 ± 8.6 (9.4 to 10.6)   | <0.001  |
| L1-S1 LL (deg)          | 52.7 ± 11.2 (51.5 to 53.9) | 55.2 ± 11.8 (54.3 to 56.1) | 0.001   |
| L1-L4 LL (deg)          | 15.8 ± 9.4 (14.8 to 16.8)  | 18.6 ± 9.7 (17.9 to 19.3)  | <0.001  |
| L4-S1 distal LL (deg)   | 36.9 ± 8.2 (36 to 37.8)    | 36.6 ± 8.7 (36 to 37.3)    | 0.64    |

\*The values are given as the mean and the standard deviation, with or without the 95% confidence interval in parentheses.

from 51° in prepuberty to 56° at the end of growth. Interestingly, most of the changes occurred in the proximal LL (L1-L4 segment). A possible hypothesis is that these changes in proximal LL are a response to the PI increase. The relationship between the amounts of LL and PI has been widely reported<sup>20,21</sup>, and the latter has shown to be specifically linked to the amount of proximal LL, with the distal part remaining constant and independent of PI<sup>22</sup>. Our results confirm this observation, as the PI increase was followed by a proximal LL increase, whereas no significant change occurred in the distal LL.

According to the slope-to-slope concept, the LL increase induced a TK increase. Most of the changes in thoracic curvature occurred during the growth deceleration phase (Group 4), as a final postural adjustment after changes in pelvic parameters and LL. An interesting point is that these modifications only occurred in the distal TK, immediately above the changes in LL. These results are in line with previous literature, as relationships between proximal LL and distal TK have already been described in the onset of spine deformity<sup>23</sup>.

Several authors have reported the change in sagittal curvature during growth. Voutsinas and MacEwen reported data from 670 healthy subjects and found slight increases in TK (+1.8°) and LL (+4.4°) from 5 to 20 years of age<sup>24</sup>. Cil et al. reported a similar result based on an analysis of 151 healthy children<sup>15</sup>. They found changes in TK according to age (mean increase, 0.7° per level), with the peak of change between the ages of 13 and 15 years, and changes in LL (mean increase, 2° per level), with the peak of change between the ages of 10 and 12 years. Our results are consistent, as we found that LL changed earlier than TK. Finally, Mac-Thiong et al. compared subjects before and after the age of 10 years and found a 3.8° increase in TK and 3.9° increase in LL in older subjects<sup>8</sup>. Interestingly, they found only small changes in PI and PT, and no change in SS, which is consistent with our results. Our study builds upon theirs, but using skeletal maturity groups aids in understanding the exact timing of change for every parameter.

We found no major difference between boys and girls. It is interesting to note that girls had a more anteverted pelvis, resulting in increased LL, especially at its proximal part.

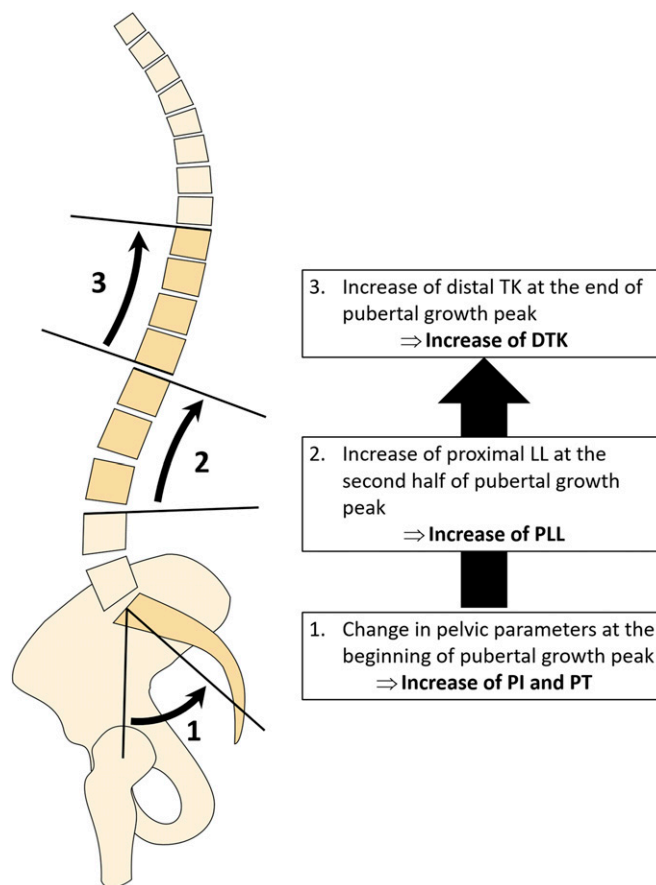


Fig. 6  
The cascade of changes in spinal sagittal alignment over the growth stages. DTK = distal TK, and PLL = proximal LL.

However, this did not lead to a distal TK increase, regardless of the growth stage.

In total, sagittal alignment variations during growth appeared to represent a cascade of changes occurring during skeletal maturation. The first change involved the pelvis (PI and PT increase), followed by proximal LL and distal TK increases and, finally, distal TK increase (Fig. 6). The current study showed that most of the spinal shape changes during growth occurred around the thoracolumbar junction, and the proximal and distal ends of the spine remained constant.

This study had some limitations. First, it was a cross-sectional study. From a methodological point of view, a longitudinal study would have been stronger. However, the use of a large data set of subjects allowed us to draw conclusions regarding the global population. Second, the use of the Risser sign and age for growth assessment is debatable. Indeed, use of Sanders Hand Score might have been more precise, but our retrospective study design did not allow us to utilize such data, which were not available. Another limitation to consider was the differences in size between groups. Indeed, Group 5 was overrepresented with 401 subjects (38% of the entire cohort), which is easily explained by the fact that subjects were recruited for adolescent scoliosis screening. However, the number of subjects in every group was large enough to draw relevant conclusions. Finally, we were not able to collect any data about ethnicity. As spinal shape may differ according to ethnicity, our results may only apply to a Western European population. Further studies are warranted to validate our results in other populations.

Although statistical analysis revealed significant changes in several parameters, the clinical relevance of the findings can be questioned. Indeed, changes were very small ( $2^\circ$  to  $5^\circ$ ), close

to the measurement error, but the pattern of changes was consistent across age groups and was explainable anatomically. Therefore, another conclusion that can be drawn from our large series is that, despite significant changes during skeletal maturity, the modifications in spinal curvatures are not large enough to be considered in clinical practice and to impact our surgical planning, especially when dealing with an immature child (early-onset scoliosis with growing-rod treatment), rather than a mature patient with scoliosis for whom final fusion is being considered. ■

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