3D quasi-automatic spine length assessment using low dose biplanar radiography after surgical correction in thoracic idiopathic scoliosis

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A B S T R A C T

Objective: Surgical correction of thoracic scoliosis leads to a height improvement. Our objectives were to assess how the linear and developed spinal column lengths relate to the frontal and sagittal parameters after a surgical correction of thoracic idiopathic scoliosis, and whether the measurement of these lengths is reliable using quasi-automatic 3D reconstruction methods with biplanar X-rays.
Methods: Consecutive children with thoracic idiopathic scoliosis who underwent spinal fusion surgery and biplanar pre and postoperative X-rays in free-standing position were included prospectively. Quasi-automatic computed 3D reconstructions of the spine were done using a previously validated technique and allowed the automatic computation of geometrical spinopelvic parameters including OD-pelvis, linear, and developed T1-T12 and T1-L5 lengths.
Results: Thirty patients with scoliosis were included, and 240 reconstructions were performed (2 operators x2 repetitions x30 patients pre and postoperative). The main thoracic Cobb angle, T1-T12, T1-L5 linear and developed distance, OD-pelvis were significantly improved ($p < 0.001$). The gain of the main thoracic Cobb angle (31.6°;SD = 9°) was correlated to the gain of the linear distance T1-T12 (15.3 mm;SD=7.3 mm)(rho = 0.76;$p < 0.0001$) and T1-L5 (24.7 mm;SD = 8 mm)(rho = 0.64;$p < 0.0001$). The postoperative change of developed length between T1-L5 represented 41% of the gain in linear distance between the same vertebrae. Similarly, the gain of T1-T12 developed length was 50% of linear T1-T12 height gain. Both differences were significant ($p = 0.01$). Absolute bias using Bland & Altman plots was lower than 1 mm for linear distance (0.1%) and lower than 2 mm (0.3%) for developed distance.
Conclusion: The gain in spinal length is correlated to the thoracic Cobb angle correction in the surgical treatment of idiopathic thoracic scoliosis. The new significant finding is that the developed spinal height gain represented approximately a little less than 50% of the linear spinal height gain and these parameters were reliable from a 3D quasi-automatic reconstruction of biplanar X-ray.

1. Introduction

Scoliosis is a three-dimensional spinal deformity distinguished by lateral deviation and axial rotation of the vertebrae. For idiopathic thoracic scoliosis, surgery is suggested for a progressive and significant curvature with a thoracic Cobb angle greater than 45° [1]. The objective of the surgery is to obtain a satisfactory correction. Accordingly, the patient has a harmonious sagittal and frontal alignment (i.e. thoracic kyphosis corresponding to the patient's overall alignment and even shoulders) [1]. The second objective is to avoid the progression of scoliosis, which could evolve towards a restrictive respiratory syndrome. Surgical fusion correction can lead to a considerable improvement in height, from 27 to 46 mm [2–7]. Contrary to classical radiographic parameters (such as Cobb angle, sagittal or spinopelvic parameters), the

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Fig. 1. Pre (a) and postoperative (b) biplanar X-ray of idiopathic thoracic scoliosis. Postoperative biplanar X-ray illustrating linear and developed length (c).

assessment of the radiographic height gain is not calculated routinely. Several studies [2–7] have focused on the measurement of the spine length but also the height gains related to surgical correction. In most studies, the height gain is correlated with the Cobb angle correction [2–6] or the number of fused vertebrae [3–6]. However, there are no studies that focus on the relationship between height gain and the 3D frontal and sagittal alignment correction. Moreover, in previous studies, only linear length (i.e., a straight line from the upper to the lower endplate of the measured lengths) was assessed, but no data were available on developed length (i.e., the curve passing through the middle of each vertebra). Besides, none of these studies used 3D quasi-automated reconstructions from low dose biplanar X-rays. Indeed, it has been shown that cumulative radiation exposure in the monitoring of scoliosis can induce cancerous lesions [8,9]. Low dose biplanar X-rays make it possible to reduce the induced dose by at least 10 times while performing a standing X-ray in the functional position, with a ten-second acquisition time [10]. Recent studies have shown the reliability of quasi-automated reconstructions in the measurement of spinal parameters [11], but none have focused on the linear and developed length of the spine and severe scoliosis.

Therefore, we addressed the question of how the linear and developed spinal column lengths relate to the frontal and sagittal parameters after a surgical correction of thoracic idiopathic scoliosis, and whether the measurement of these lengths is reliable using quasi-automatic 3D reconstruction methods with biplanar X-rays.

2. Materials and methods

2.1. Subjects

An institutional ethics review board (C.P.P. Île de France IV: Records 14 409) approved this prospective single-center study. Parents and children were informed about the protocol and consented to participate before inclusion. Consecutive children with thoracic idiopathic scoliosis (Lenke 1 and 3) [12] who underwent posterior spinal fusion surgery at our center between January 2017 and July 2018 were included. Spinal Surgery was proposed if frontal thoracic Cobb angle was higher than 40°, Risser sign higher than 1 [13], closed triradiate cartilage and at least one of clinical trunk malalignment and/or 20° lower thoracic hypokyphosis. The exclusion criteria were a transitional anomaly, an antecedent of spine surgery, halo traction before the fusion and an incomplete follow-up. Weight and height using a wall stadiometer were collected.

2.2. Surgical technique

A single spine surgeon performed the surgical interventions, using an all-screw fixation (except a transverse hook at the top of construct) in all patients under somatosensory and motor evoked potentials monitoring. Correction was done by a posteromedial translation method [14]. The number of levels instrumented was reported.

2.3. Imaging data assessment

All patients underwent frontal and sagittal biplanar radiographs (EOS™ system, EOS imaging, Paris, France) [15,16] in a free-standing position [17] preoperatively and 4 months after surgery. A lack of preoperative and postoperative imaging studies and improper positioning during biplanar radiographs was an exclusion criteria. Risser sign [13] was collected. A Risser's sign greater than 1 means that more than 25% of the ossification core of the iliac crest is visible on radiography. Quasi-automatic computed 3D reconstructions of the spine were done using a previously validated technique [11,18]. Briefly, the operator selected a few anatomical landmarks on the frontal and lateral radiographs: sacral plate, left and right acetabula, the spinal midline through the center of all vertebral bodies from the odontoid apophysis of C2 to the L5 lower endplate. The upper endplate of C7 and lower endplate of T12 were also selected in the lateral view, while the two endplates delimiting the main scoliotic curve were selected in the frontal view. The junctional levels of the main curve were defined to obtain the maximization of Cobb angle, and they were often characterized by a local discontinuity of vertebral axial rotation (i.e., a sudden change of vertebral axial orientation). An automatic algorithm provided an initial solution of 3D reconstruction, on which the operator could perform fast manual adjustment of vertebrae to improve accuracy. The reconstruction took about 5 min on average.

The 3D reconstruction allowed the automatic computation of geometrical spinopelvic parameters: main thoracic curve Cobb angle (°), T1-T12 developed distance (mm), T1-L5 developed distance (mm), T1-T12 linear distance (mm), T1-L5 linear distance (mm) (Fig. 1), odontoid (OD)-pelvis distance between the most superior point of the odontoid process of C2 (OD) and the center of the bi-coxofemoral axis (HA) (mm), and OD-HA frontal angle corresponding at the angle between the vertical and the line joining OD and HA (°), OD-HA sagittal angle (°) and T4-T12 kyphosis (°).

2.4. Statistical analysis

Pilot data was used to estimate that a sample size of 27 patients

Table 1
Pre and postoperative radiographic measurements. Results are presented as mean (± one standard deviation). The changes between the post and preoperative measurements are indicated in the column difference. The - sign indicates a decrease in the value of the measured parameter and the + sign an increase.

Measurements	Preoperative	Postoperative	Difference	*p*-value
Cobb angle (°)	50.3 (± 9)	18.7 (± 6)	- 31.6 (± 9)	< 0.0001
T1-T12 developed distance (mm)	237 (± 12)	244.2 (± 12)	+ 7.2 (± 12)	< 0.0001
T1-L5 developed distance (mm)	392.8 (± 19)	402.5 (± 18)	+ 9.7 (± 14)	< 0.0001
T1-T12 linear distance (mm)	216.8 (± 14)	232.1 (± 11)	+ 15.3 (± 7.3)	< 0.0001
T1-L5 linear distance (mm)	360.5 (± 21)	385.2 (± 19)	+ 24.7 (± 17)	< 0.0001
OD-pelvis (mm)	598.7 (± 29)	622.8 (± 26)	+ 24.1 (± 10)	< 0.0001
Frontal OD-HA (°)	1.4 (± 1)	0.9 (± 0.6)	- 0.5 (± 0.4)	0.62
Sagittal OD-HA (°)	2.2 (± 1)	2.6 (± 1.7)	+ 0.4 (± 0.5)	0,42
T4-T12 kyphosis (°)	24 (± 15)	30.3 (± 7)	+ 6.3 (± 5)	< 0.0001

would allow to detect a change of T1-T12 developed length with a statistical power of 0.9 (calculation made with GPower). Normality of data distribution was verified with Shapiro-Wilk normality test, and differences between pre and postoperative parameters were analyzed with paired t-tests for normal variables and Wilcoxon rank tests for non-normal ones. Correlations between parameters were tested with the Spearman test. Results were reported with Spearman's rho, *p*-value, and confidence interval (CI). Statistical significance was set at 0.05. Reproducibility was evaluated according to the ISO 5725 standard in terms of standard deviation of uncertainty (SD) and coefficient of variation (CV): two spine surgeons independent of the analysis results repeated the 3D reconstruction of 30 patients twice at a 1-month interval between the two sessions. The order of the reconstructions, between the two repetitions, was anonymous and randomized by a third operator independent to the reconstructions. Bland-Altman plots were used to represent the limits of agreement [19].

3. Results

3.1. Cohort description

Thirty patients were included (7 with Lenke type 1 curves and 23 with Lenke type 3). The mean age at surgery was 14.9 years old (SD = 1.7; range from 11 to 17) and the mean body mass index was 19.2 kg m^{-2} (SD = 3.7; range from 7.9 to 28). The mean Risser sign was 3.4 (SD = 1.2; range 2 from to 5). Overall, 240 quasi-automatic reconstructions were performed (2 operators x 2 repetitions x 30 patients pre and postoperative).

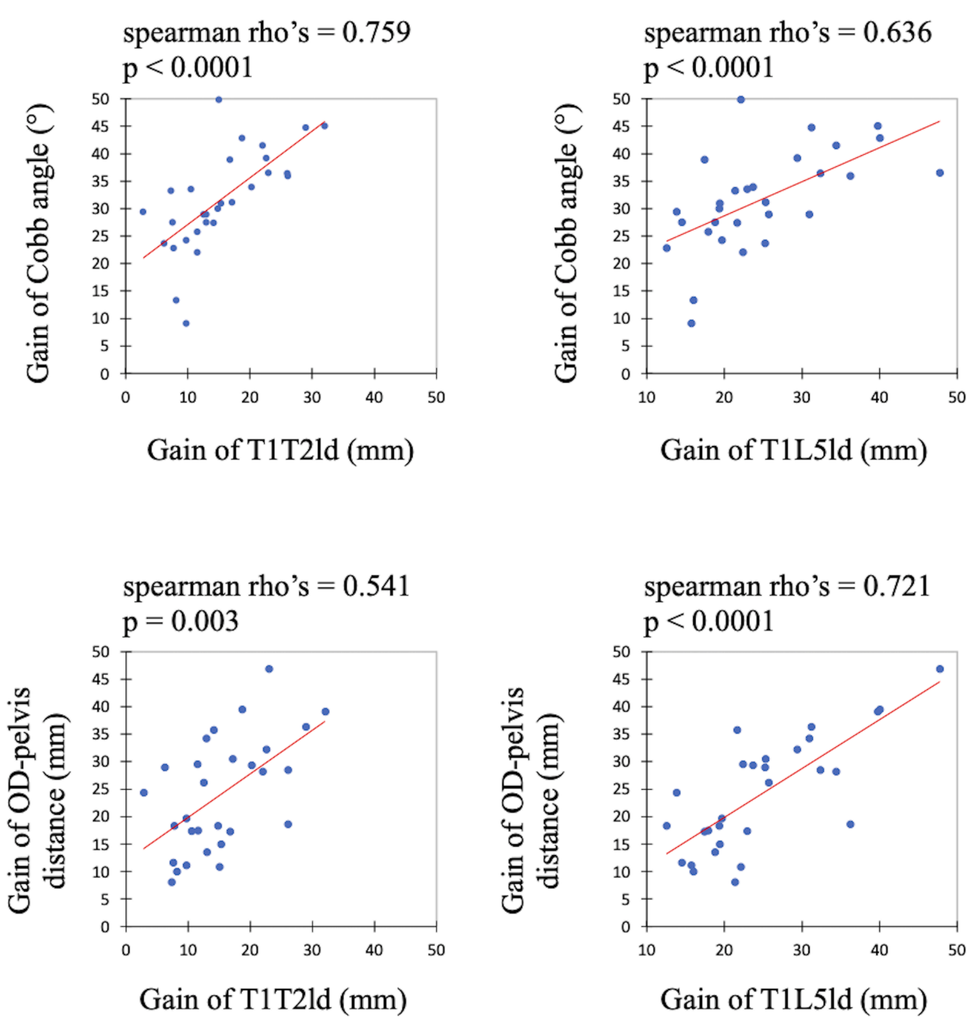

Fig. 2. Scatter plot graph representing the significant correlation between parameters (the mean gain of Cobb angle, OD-pelvis distance, T1T12, and T1L5 linear distance.

Table 2
Pre and postoperative reproducibility of radiographical measurements. Results are presented as one standard deviation (Coefficient of variation in percentage).

Measurements	Preoperative	Postoperative
Cobb angle (°)	3.4 (7.4)	4.2 (7.8)
T1-T12 developed distance (mm)	0.9 (0.3)	1.1 (0.5)
T1-L5 developed distance (mm)	2.2 (0.6)	2.5 (0.7)
T1-T12 linear distance (mm)	1.5 (0.5)	1.3 (0.7)
T1-L5 linear distance (mm)	2.4 (0.7)	2.5 (0.7)
OD-pelvis (mm)	1.3 (0.1)	1.4 (0.3)
Frontal OD-HA (°)	0.2 (ns)	0.1 (ns)
Sagittal OD-HA (°)	0.1 (ns)	0.1 (ns)
T4-T12 kyphosis (°)	3.1 (13.2)	3.3 (13.4)

3.2. Radiographic parameters

The main thoracic Cobb angle, T1-T12 linear and developed distance, T1-L5 linear and developed distance, OD-pelvis, and T4-T12 kyphosis were significantly improved by surgery ($p < 0.001$); values are shown in Table 1. The gain of the main thoracic Cobb angle (31.6°; SD = 9; range from 15.2° to 49.9°) was correlated to the gain of the linear distance of T1-T12 (15.3 mm; SD = 7.3; range from 6.2 to 32 mm) (rho = 0.76; $p < 0.0001$; CI 95% = 0.50–0.89) and T1-L5 (24.7 mm; SD = 8; range from 12.5 to 47.8 mm) (rho = 0.64; $p < 0.0001$; 95%CI = 0.32–0.82). The mean gain of OD-pelvis distance was 24.1 mm (SD = 10; range 12.1 to 46.9 mm) and this gain was correlated to T1-T12 (rho = 0.54; $p = 0.003$; CI 95% = 0.19–0.77) and T1-L5 (rho = 0.72; $p < 0.0001$; 95%CI = 0.44–0.87) linear distances. These relationships are presented in Fig. 2. No correlations were found between spinal length (linear and developed) and preoperative height (rho = 0.40; $p = 0.091$), age of surgery (rho = 0.28; $p = 0.701$), Risser sign (rho = 0.19; $p = 0.101$), or the number of levels instrumented (rho = 0.22; $p = 0.201$). The postoperative gain in developed T1-L5 length represented 41% of the linear height gain (SD = 18%; Coefficient of variation = 41.4) and the gain of T1-T12 developed length was 50% of linear thoracic height gain (SD = 20%; Coefficient of variation = 40). The difference between the developed and linear lengths was significant ($p = 0.01$).

3.3. Reliability

Table 2 shows pre and postoperative reproducibility evaluations. There were no differences between pre and postoperative uncertainty ($p = 0.710$). Bland-Altman plots for height assessment are represented in Fig. 3. Absolute bias was lower than 1 mm for linear distance (0,1%) and lower than 2 mm (0,3%) for developed distance.

3.4. Discussion

In the surgical management of thoracic of thoracic adolescent idiopathic scoliosis, the physician strives to use objective, reproducible, and reliable criteria to plan the correction and assess its outcome. This is even more relevant in the current era of shared decision-making,

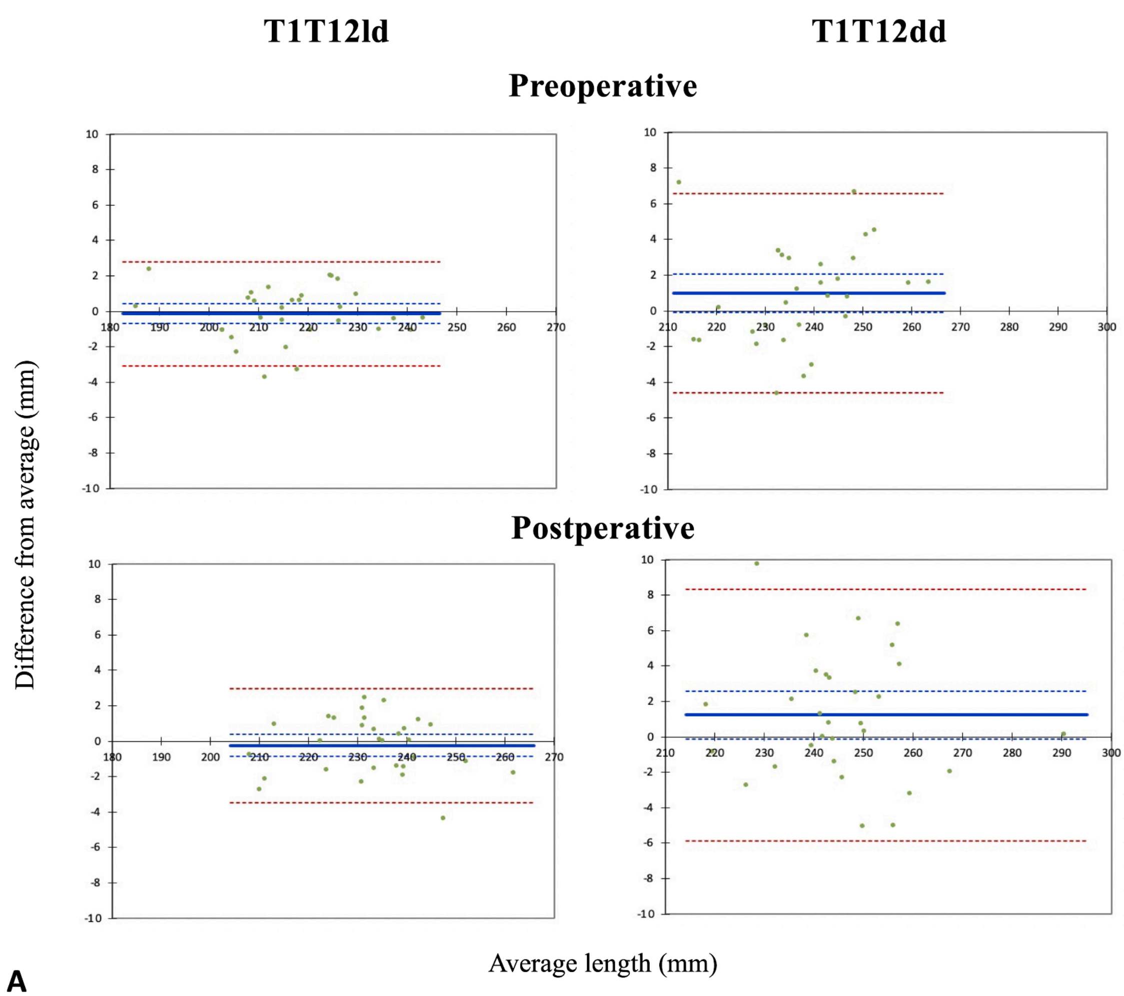

Fig. 3. Bland & Altman plots representing the limits of agreement of length measurement (A: T1-T12; B: T1-L5; C: OD-pelvis). The horizontal red dotted line represents 95% confidence intervals of measure. The horizontal blue dotted line represents 95% confidence intervals of bias and the average bias is represented by the continuous blue horizontal line. ld = linear distance; dd = developed distance.

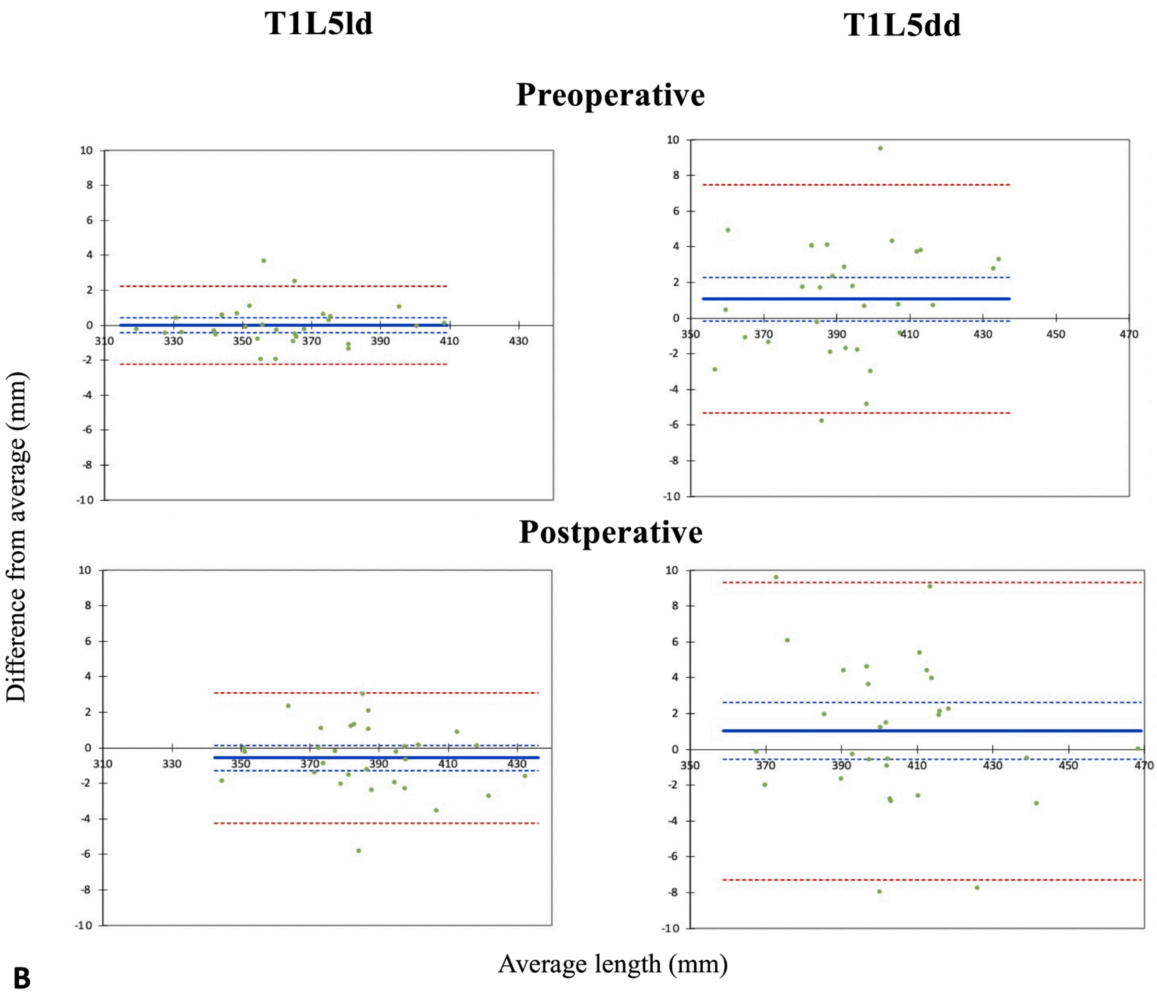

Fig. 3. (*continued*).

especially considering that correction of global alignment [20] and scoliotic curvatures can be linked to postoperative patient satisfaction [21]. The advantage of this 3D technique is that it allows to, simultaneously, calculate linear and developed spine length as well as the classical frontal and sagittal parameters.

Although clinical height gain does not motivate surgery, it does answer an important question frequently asked by patients and their families. In our series, the height gain was 24.1 mm and correlated to the main Cobb angle. The average linear height gain and the factors correlated to spinal length gain found in the literature are summarized in Table 3 [2–7]. The different 2D measurement methods reported an average gain ranging from 27 mm to 46 mm but the average correction Cobb angle (ranging from 35° to 45°) was a slightly better than ours. We did not find a link between height gain and number of vertebrae fused compared other studies [3–6]. Our hypothesis is that we did not perform selective arthrodesis, so that the differences between the fused levels are consequently small as in the study by Morin et al. [7]. The frontal curvature correction is strongly correlated to the height gain [2–6]. However, a significant frontal correction or an excessive thoracic kyphosis is a risk factor for neurological complications [22]. The relationship between thoracic kyphosis and height gain remains unresolved. Most of the studies concern adolescent idiopathic scoliosis of less than 90 °Cobb angle and the patients included tend to have a flat thoracic back profile [23]. Although many authors [3–7] report the link between height gain and the number of fused vertebrae, Risser Sign, or demographics data, we did not confirm these findings. A correlation with OD-HA has not been found but our study includes only thoracic scoliosis, and it would be interesting to explore this possible correlation in thoraco-lumbar or lumbar curvatures. Indeed, these are curvatures responsible for frontal malalignment despite of lower Cobb angles [24].

The second relevant and new finding is that the developed T1-L5 height gain represented around 40% of the linear height gain and the gain of T1-T12 developed was around 50% of linear thoracic height gain. In addition, the inter-individual variation is high with variation coefficients around 40. Our hypothesis to explain this result is that the height gain is mainly related to the correction, but also to the distraction of the soft tissues and the increase in intervertebral disk height. Biomechanical disturbances of the intervertebral disk are partially reversible [25] and could be responsible for an increased disk height. At the same time, the soft tissues (i.e., ligaments and muscles) could also be stretched by the correction. It would be interesting to know whether there is a link between soft tissue lengthening and postoperative muscle pain. Finally, it seems unlikely that there is an intra-bone lengthening effect. However, the question that remains unanswered is to determine the location of this variation between the developed and linear height gain. Does it occur in the junctional level? or in the apical level? is it homogeneous along the column? In addition, there is a difference in the proportion of height gain developed between the thoracic segment alone and the thoracolumbar segment. Our explanation is that the thoracic curvature was predominantly the largest in our series.

The third significant point is the reliability of radiographic outcomes measurement. For our study with 4 repeated measurements and a sample of 60 radiographs (i.e. 30 preoperative and 30 postoperative), the statistical power of the reproducibility study is 0.9 [26]. Spine 3D

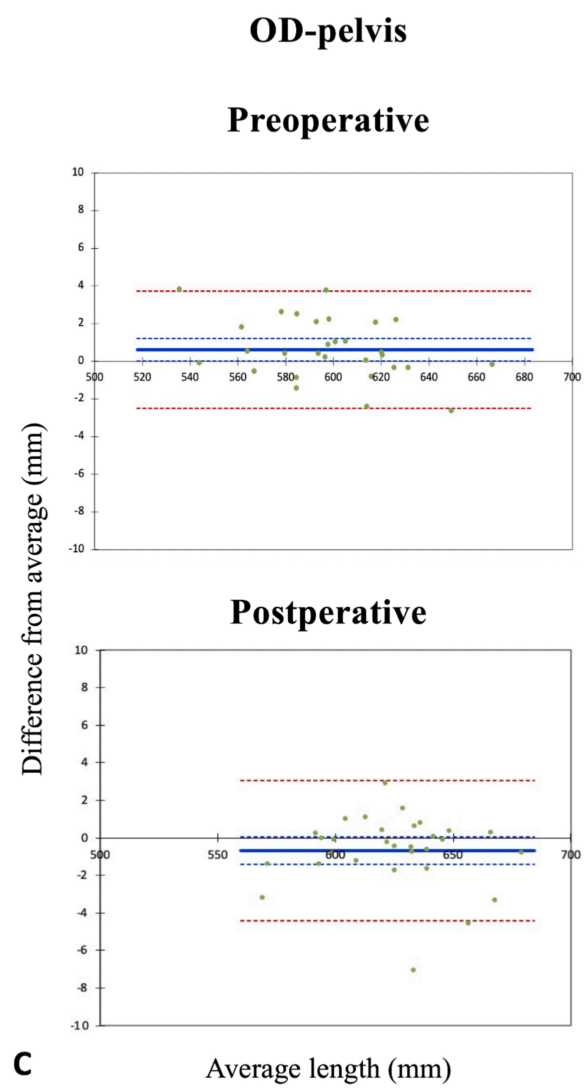

Fig. 3. (*continued*).

Table 3
Literature review of spinal length gain after posterior correction and fusion surgery in adolescent idiopathic scoliosis.

Authors(year)	Length measurement	Methods of measurement	Number of patients included	Spinal length gain	Factors correlated to spinal length gain
Watanabe et al. (2012) [2]	T1-L5 linear	Frontal standing X-ray	164	32.4 mm (SD = 10.8)	Correction of the Cobb angle
Sarlak et al. (2012) [3]	Standing Clinical height	Stadiometer	36	28.53 mm	Preoperative Cobb angle Postoperative Cobb angle Preoperative apical vertebral translation Number of vertebrae fused
Hwang et al. (2013) [4]	Standing Clinical height	Stadiometer	447	30 mm (SD = 16)	Preoperative Cobb angle Number of vertebrae fused Presence of osteotomies Correction of sagittal curvature
Spencer et al. (2014) [5]	L1-L5 linear	Frontal standing X-ray	116	27.1 mm (SD = 3)	Preoperative standing height Number of vertebrae fused Correction of the Cobb angle
Van Popta et al. (2015) [6]	C7-L5 linear	Lateral standing X-ray	104	46.6 mm (SD = 21.3)	Preoperative Cobb angle Preoperative standing height Number of vertebrae fused
Morin et al. (2020) [7]	Standing and sitting clinical height	Stadiometer	116	42 mm (SD = 18)	Preoperative standing and sitting height Risser Test Age

reconstruction is quasi-automatic, taking less than 5 min, and accessible in routine clinic. Biplanar radiographs and scanning x-ray technology present several advantages; for instance, they significantly reduce the magnification effects due to the distance of the patient from the transmitter and completely removes vertical magnification. In the EOS booth, the patient's position and spinal morphology can be reliably estimated and accounted for, and the vertical spinal length can be measured accurately between vertebral endplates. Indeed, Morin & al. described previously a good correlation between height gain radiographic and clinical measure with an absolute difference of 0.36 ± 0.3 cm [7]. Nevertheless, no 3D reconstruction was done in this previous study, and the 3D approach allows measuring the spinal developed length, which is not accessible in conventional radiographs, due to the complex morphology of the scoliotic spine. The other advantage of making 3D measurements compared to traditional measurements is that we can apply our analysis to other parameters from reconstructions of the axial plane [18] or the outer envelope and the position of the center of mass [27].

The measurements presented in this study complement the simple measurements of the frontal Cobb angle and sagittal curvatures. They can help the clinician to calculate the linear and developed length of the spine as well as to study its malalignment in relation to the femoral heads (OD-HA angle). In the case of early-onset scoliosis, it is useful to calculate the T1-T12 distance to best assess respiratory function and guide the age of the arthrodesis. Indeed, decreasing thoracic height could result in restrictive lung dysfunction [28,29]. It would appear that a T1-T12 distance of 22 cm leads to asymptomatic lung status in adulthood [30]. Another application is severe scoliosis (Cobb angle is over 80°), where it may be useful to study the gain in height obtained by the halo preparation and to plan the operation date accordingly [31].

Our study has certain limitations. Our quasi-automatic reconstruction and parameter analysis method is based on an algorithm that is only applicable to biplanar radiographs. Despite the 240 reconstructions analyzed, only 30 patients were included. To improve the accuracy of the measurements, the sample size should be increased. However, this is the first study to focus on developed and linear height measurements by quasi-automatic reconstruction in severe scoliosis. Finally, postoperative x-rays were acquired 4 months after surgery; further adaptation of patient posture could have occurred later.

The gain in length of the thoracic and thoraco-lumbar spine are correlated to the correction of the thoracic Cobb angle in the surgical treatment of idiopathic thoracic scoliosis. The new significant finding is that the developed spinal height gain represented approximately a little less than 50% of the linear spinal height gain but with strong inter-individual variation. Moreover, the linear and developed spinal length measurements with 3D quasi-automatic reconstructions of biplanar X-ray are reliable parameters in pre and postoperative and can use routinely.

4. Funding

None.

5. Ethical approval

Parents or adults signed informed consent, which was approved by the national ethics committee (C.P.P. Île de France IV: Records 14 409).

Declaration of Competing Interest

None.

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