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Global Sagittal Alignment and Proximal Junctional Kyphosis in Adolescent Idiopathic Scoliosis

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Abstract

Study Design: Case-control study.

Objectives: To analyse global sagittal alignment including the cranial center of mass (CCOM) and proximal junctional kyphosis (PJK) in adolescent idiopathic scoliosis (AIS) patients treated with posterior instrumentation.

Summary of Background Data: PJK plays an important role in the global sagittal alignment in AIS patients. Maintaining the head above the pelvis allows for a minimization of energy expense in ambulation and upright posture. Numerous studies have been performed to understand the PJK phenomena in AIS patients. However, to our knowledge, no study performed on AIS patients included the head in the analysis of global sagittal alignment and PJK.

Methods: This study included 85 AIS patients and 51 asymptomatic adolescents. Low-dose bi-planar radiographs were acquired for each subject preoperatively and at the two-year follow-up. Two global sagittal alignment parameters were calculated, that is, the angle between the vertical and the line joining the center of the bi-coxofemoral axis (HA) and either the most superior point of the dentiform apophysis of C2 (OD) or the cranial center of mass (CCOM).

Results: Among normal adolescents, the average OD-HA and CCOM-HA angles were $-2.3° \pm 2°$ and $-1.5° \pm 1.8°$, respectively. Among AIS patients, the average OD-HA and CCOM-HA angles were, respectively, $-2.3° \pm 1.9°$ and $-1.3° \pm 1.8°$ preoperatively and $-2.8° \pm 1.7°$ and $-1.9° \pm 1.7°$ at the last follow-up. Overall, 13% of the patients developed PJK postoperatively. Case-by-case analysis showed that adjusting the thoracic kyphosis and the compensations required to maintain this constant could provide explanatory elements.

Conclusions: OD-HA and CCOM-HA angles remain almost constant among the normal group and patients, pre- and postoperatively, whether PJK or non-PJK. Five patients without PJK and only one patient with PJK produced abnormal values relative to the asymptomatic subjects. Therefore, it could be concluded that PJK is a compensation mechanism, which allows for CCOM-HA and, to a lesser extent, OD-HA to remain invariant.

Level of Evidence: Level III.

Keywords: AIS; 3D reconstruction; PJK; Global balance; Patient-specific

Introduction

It is well known that adolescent idiopathic scoliosis (AIS) is a three-dimensional deformity of the trunk and spine characterized by a spinal curve or curves in the patient's coronal plane. Nevertheless, the sagittal plane represents an important aspect of the patient's balance [1]. Proximal junctional kyphosis is a recently recognized phenomenon in adolescents after AIS surgery. As reported by Yan et al., the incidence of proximal junctional kyphosis (PJK) in adolescent patients was estimated at 11%, with a

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IRB Approval: This study was approved by the Hospital's Research Ethics Committee.

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range of 0 to 55% depending on the study, and revision surgery was needed in 10% of these cases [2]. The etiology of PJK is likely multifactorial, with risk factors including thoracoplasty, hybrid instrumentation (proximal hooks and distal pedicle screws, pelvic fixation), integrity of the posterior ligaments, and a preoperative large sagittal thoracic Cobb angle (T5−T12 > 40°) [3]. Kim et al. reported that a greater immediate postoperative thoracic kyphosis angle decrease and male sex correlated significantly with PJK [4].

The head's center of gravity passes in front of the cervical spine, thus inducing a non-negligible torque on the spine, considering that the head represents about 7% of total body weight [5]. Therefore, the global spine alignment including the head should be considered during the surgical planning of posterior instrumentation.

Type 1 and type 2 Lenke curves are associated with abnormal thoracic sagittal alignment, but it has been shown that thoracic hypokyphosis and cervical hypolordosis, often observed in AIS, can be improved postoperatively [6-8]. Patients with thoracic hypokyphosis usually compensate with cervical hypolordosis. Hayashi et al. reported that a preoperative cervical lordosis angle (CLA) lower than −5° and a preoperative thoracic kyphosis lower than 10° were significantly associated with postoperative cervical hyperkyphosis [9]. Wang et al. reported that the cervical sagittal alignment in AIS patients was related with lumbar lordosis and particularly with thoracic kyphosis [7]. It has been reported in many studies that the cervical sagittal alignment correlate with health-related quality of life (HRQOL) in AIS patients [10,11], and that suboptimal sagittal alignment after corrective surgery, such as decreased thoracic kyphosis, is a possible cause of lumbar or cervical spinal degeneration and junctional malalignment [1].

Cotrel-Dubousset instrumentation with concave derotation technique by rod precontouring was able to restore thoracic kyphosis for patients with hypokyphotic spines, preserving or re-establishing normal lumbar lordosis in a considerable percentage of patients [12-14]. The purpose of this series was to analyze global sagittal alignment including the cranial center of mass (CCOM) and PJK in AIS patients treated with this technique.

Materials and Methods

Subjects

After Ethics Committee approval, the data collection of 85 patients with a minimum of two years' follow-up was carried out retrospectively. The age range was 12−18 years at the time of surgery. All surgeries were performed at the same center by the same surgeon between 2008 and 2014. Only AIS patients treated with posterior fusion with all−pedicle screw constructs were considered. No revision

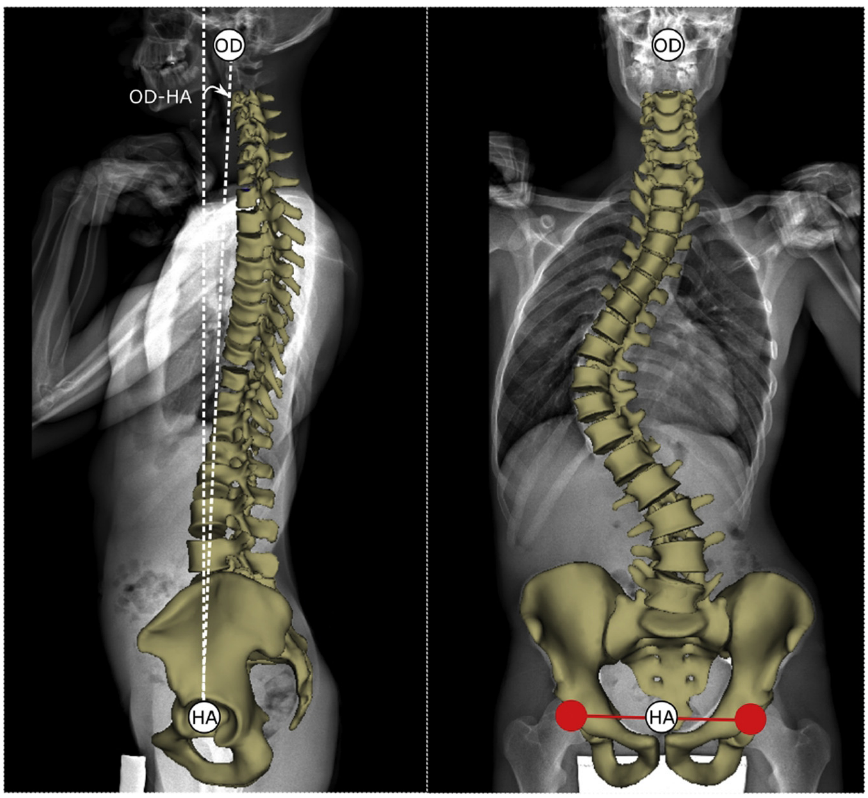

Fig. 1. 3D reconstruction of pelvis and spine (from C3 to Sacrum). OD is the most superior point of dentiform apophyse of C2, HA is the center of the bi-coxofemoral segment. OD-HA is the angle between the vertical line from HA and the line joining OD and HA.

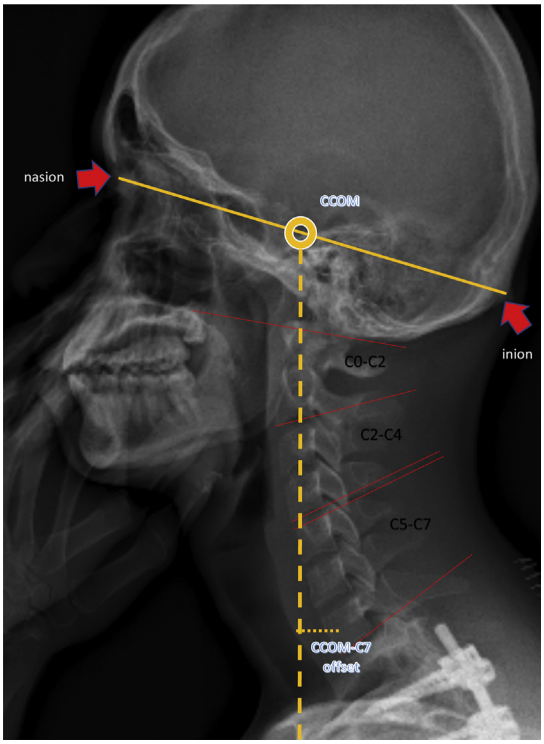

Fig. 2. CCOM, Cranial Center Of Mass is midway on the nation-inion line. CCOM-C7 offset is the distance between the vertical line from CCOM and center of C7 body.

cases were included in this study. Proximal fixations ended at the T2−T4 vertebral level. The spine was exposed proximally with care. No violation of facets superior to the UIV occurred, and no resection of interspinous ligament either.

The radiobiologic data of 51 asymptomatic adolescents with age ranged from 12 to 18 years old were also retrospectively collected to evaluate normality corridors of clinical parameters.

Protocol

Bi-planar radiographies were acquired with a low-dose x-ray device (EOS Imaging, Paris, France) [15]. Images were acquired with the patients standing upright with the hands resting on the clavicles and keeping forward eye gaze as described by Faro et al. [16]. Patients with inadequate position were excluded.

Radiologic examinations were performed preoperatively and at the last follow-up for all patients, whereas radiographs were also acquired immediately after surgery and three months after surgery for 8 of the 11 patients who developed PJK.

The EOS system was validated to provide reliable 3D reconstruction of spine deformity [17,18]. 3D reconstructions of pelvis, spine (from C3 to L5) and the most superior point of dentiform apophyse of C2 (OD) was

Table 1
Computed parameters of control group and AIS patients before surgery and at two years follow-up.

Abbreviation	Parameter	Mean ± SD (healthy subjects)	Mean ± SD (AIS preop)	Mean ± SD (AIS last follow-up)	p value (AIS preop vs last FU)
CL C3−C7	Cervical lordosis C3−C7 (°)	−3.7 ± 0.1	16.6 ± 6.5	11.7 ± 7.9	.00007
OD-HA	Angle between the vertical and the line that connects OD to HA (°)	−2.3 ± 2	−2.3 ± 1.9	−2.8 ± 1.7	.009
CCOM-HA	Angle between the vertical and the line that connects CCOM to HA (°)	−1.5 ± 1.8	−1.3 ± 1.8	−1.9 ± 1.7	.003
C7-HA	Angle between the vertical and the line that connects C7 to HA (°)	−4 ± 2.1	−4.5 ± 2.2	−5.5 ± 1.9	.0003
OD-HA offset	Distance between two vertical lines that fit the OD and HA (mm)	−26.1 ± 15.3	−24.1 ± 19.3	−30.9 ± 19	.003
CCOM-HA offset	Distance between two vertical lines that fit CCOM and HA (mm)	−16.8 ± 19.6	−13.9 ± 20.3	−21.8 ± 19.6	.002
CCOM-Sacrum offset	Distance between CCOM and S1 plateau’s center (mm)	−0.7 ± 17.7	2.6 ± 18.9	−3.4 ± 18.5	.01
C7-HA offset	Distance between two vertical lines that fit the C7 body’s center and HA (mm)	−18.9 ± 20.6	−39.3 ± 19.2	−50.5 ± 17.2	.002
C7 SVA	Sagittal vertical axis (distance between C7 body’s center and S1 plateau’s center) (mm)	−8.9 ± 21.6	−22.8 ± 18	−32.1 ± 16.3	.0001
T1S	T1 slope (°)	20.1 ± 5	12.7 ± 7.9	14.1 ± 7	.1
Inclination	Angle between the vertical and the line that best fits: OD, all the vertebral body’s centers from C3 to L5, and S1 (°)	−2.8 ± 2.7	0.7 ± 20.6	11.4 ± 24	.007
CA	Cobb angle (°)	−	64.1 ± 12.4	25.4 ± 8.8	1.2*10-15
T1−T12 ky	T1−T12 kyphosis (°)	42.4 ± 12.6	32.2 ± 10.6	38.4 ± 9.8	.0001
T4−T12 ky	T4−T12 kyphosis (°)	30.2 ± 10.6	23.2 ± 11.9	24.9 ± 9.2	.3
L1−S1 LL	L1−S1 lumbar lordosis (°)	−52.1 ± 12	−55.3 ± 9.8	−55.7 ± 8.4	.8
PI	Pelvic incidence (°)	49.7 ± 11.4	50.7 ± 9.1	51.1 ± 8.5	.7
PT	Pelvic tilt (°)	9.6 ± 7.6	10.3 ± 6.9	11.1 ± 6.4	.2
SS	Sacral slope (°)	40 ± 9.4	40.4 ± 6.4	38.2 ± 7.6	.3
PJK angle	Angle between the inferior plate of UIV and the superior plate of two vertebrae above (°)	−	8.2 ± 6.2	12.9 ± 6.6	.0000003

AIS, adolescent idiopathic scoliosis; CCOM, cranial center of mass; FU, follow-up; HA, the center of the bi-coxofemoral segment; OD, the most superior point of dentiform apophyse of C2; PJK, proximal junctional kyphosis; SD, standard deviation; UIV, upper instrumented vertebra.

performed (Fig. 1). In addition, as described by Vital et al. [5], two stereo-corresponding points localizing the nasion and inion were digitized on the sagittal and coronal views in each reconstructed model to compute the CCOM (Fig. 2). 3D reconstructions were also performed for 51 healthy adolescents to determine the normality corridor of CCOM position.

The parameters analyzed in this study were described in (Table 1); all parameters were calculated in the patient's sagittal plane.

Proximal junctional kyphosis

Abnormal PJK was defined as the postoperative proximal junctional sagittal angle between the lower endplate of the uppermost instrumented vertebra and the upper endplate of two vertebrae supra-adjacent superior to 10° and increased by at least 10° relative to the preoperative measurement [3].

UIV-OD and UIV-CCOM offsets

The lever arm between the body's center of the upper instrumented vertebra (UIV) and the vertical line that passes through either the most superior point of dentiform apophyse of C2 (UIV-OD offset) or the cranial center of mass (UIV-CCOM offset).

Statistical analysis

Clinical parameters were compared for all patients before and after surgery (paired Wilcoxon tests). A Mann-Whitney *U* test was performed to analyze differences between preoperative parameters among the PJK and no-PJK groups, whereas Kruskal-Wallis tests were used to compare the healthy population with preoperative PJK and preoperative non-PJK patients.

Correlations were quantified using pairwise Spearman correlations. Nonparametric tests were used to account for the nonnormal distribution of several variables (Lilliefors normality test). The significance level was set at 0.05.

Results

Demographic data

The mean age was 15.6 years (standard deviation [SD] = 1.99 years old) for AIS patients and 16.3 years (SD = 1.7 years old) for asymptomatic adolescent subjects. Overall, there were 88.2% female (75 patients) and 11.8% male (10 patients) of AIS patients and 67% female and 33% male of asymptomatic subjects. The mean weight of AIS patients was 51.3 kg (SD = 9.5 kg) with a mean body mass index of 20 (SD = 3.7). Full sets of radiographs (preoperative, immediate postoperative, 3 months postoperative and last follow-up) were only available for eight PJK patients; for all other patients, only preoperative and last follow-up examination records were available. No differences of surgical intervention were detected to explain PJK.

Results on all parameter before surgery and at last follow-up are reported in Table 1.

Thoracolumbar and spinopelvic sagittal alignment

The average L1−S1 lordosis and pelvic tilt remained constant from the preoperative to last follow-up at −55° and 10.7° overall average values, respectively. However, this unchanged average masks significant interindividual differences: 19 (22.4%) patients had their pelvic incidence modified by more than 5° at the follow-up of two years, whereas 23 patients (27%) modified their pelvic tilt. Twenty-seven patients (32%) preoperatively versus 24 patients (28%) postoperatively were outside the normality corridor for pelvic tilt provided by Vialle et al. [19] (Fig. 3). The average T1−T12 kyphosis significantly increased by 6.2° postoperatively ($p = .0001$), thus getting closer to the values of the healthy population (42.4° ± 12.6°). Lumbar lordosis was similar in AIS patients and healthy controls, and it did not significantly change postoperation.

Head and cervical sagittal alignment

In AIS patients, cervical C3−C7 lordosis was significantly lower than in the healthy population (Table 1), and it

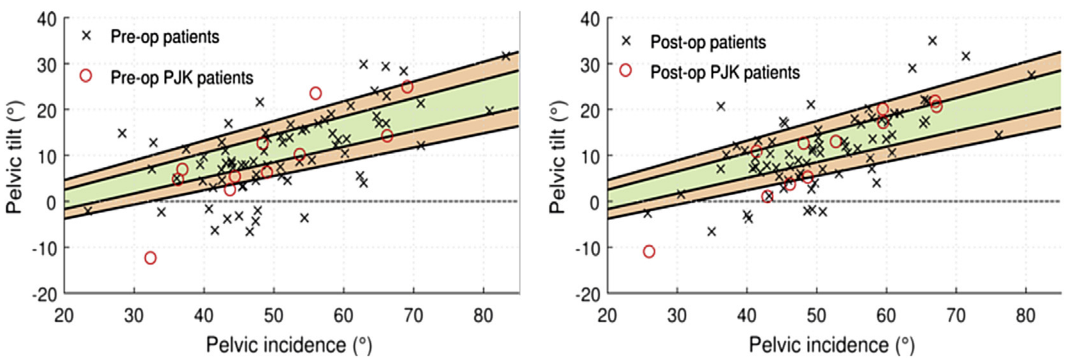

Fig. 3. Normality corridor for the pelvic tilt (PT) based on its relation with pelvic incidence (PI) provided by Vialle et al. (PT = −7 + 0.37 PI). The green band (mean + SD) and orange band (2*SD) is the corridor of normality among 51 asymptomatic adolescents.

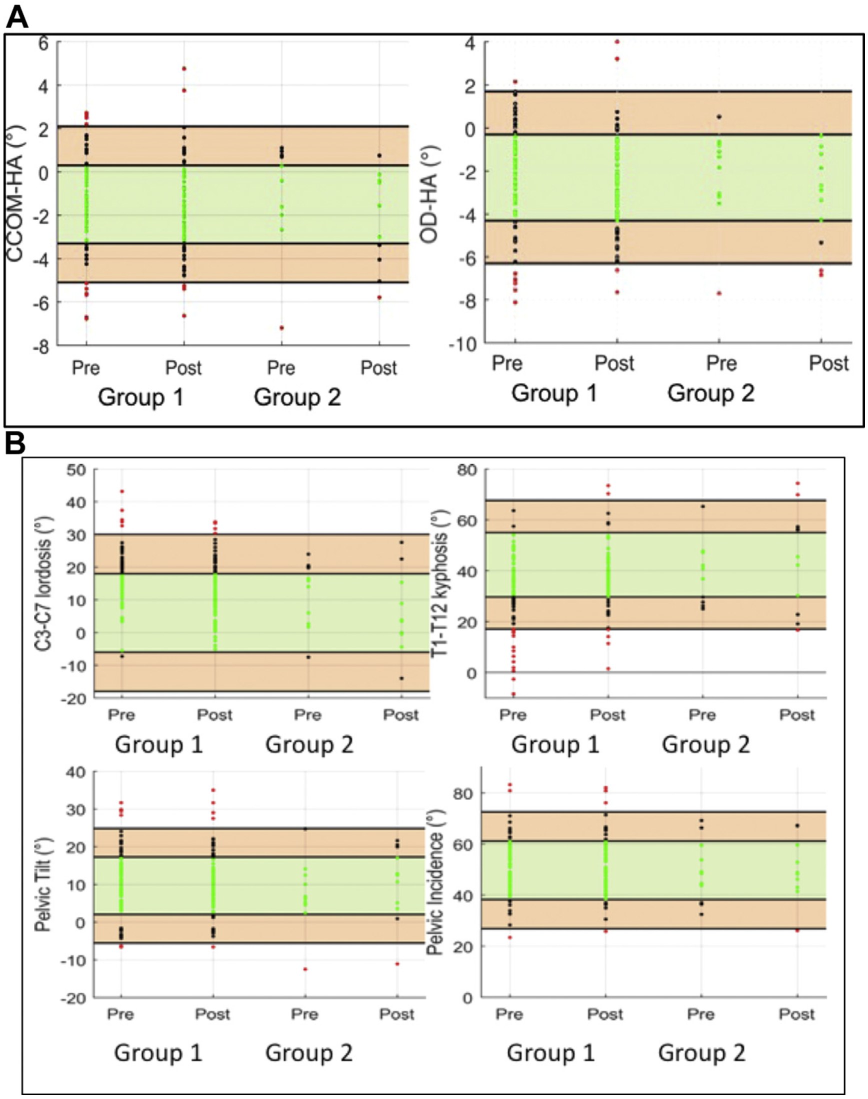

Fig. 4. Pre- and postoperative parameters in the two groups (Group 1: Non-PJK group, and Group 2: PJK group). (A) CCOM-HA (°) and OD-HA (°). CCOM-HA angle: from −3.3° to 0.3°, normal; from 0.3° to 2.1°, subnormal high; from −3.3° to −5.1°, subnormal low. (B) C3–C7 lordosis, T1–T12 kyphosis, pelvic tilt, and pelvic incidence. The green band (mean ± SD) and the orange band (2*SD) represent the corridor of normality among 51 asymptomatic adolescents. CCOM, cranial center of mass; OD, odontoid; HA, center of the bi-coxofemoral segment.

significantly increased after surgery by 4.9° ($p < .0001$), toward normal values. Among AIS patients, the average OD-HA and CCOM-HA angles were, respectively, −2.3° ± 1.9° and −1.3° ± 1.8° preoperatively and −2.8° ± 1.7° and −1.9° ± 1.7° at the two-year follow-up. Among normal adolescents, the average OD-HA angle and CCOM-HA angle were −2.3° ± 2° and −1.5° ± 1.8°, respectively (Fig. 4).

Proximal junctional kyphosis subgroup

The average PJK angle for the whole population increased between preoperative and at the last follow-up by 4.7° ($p < .0001$). Thirteen percent (11 patients; 9 female/2 male) had abnormal PJK at the last follow-up, and 36% (4 patients) of them developed PJK during the first three months following the surgery. The average age at time of surgery was 15 years (SD = 1.9). Evolution of the proximal junctional angle among the patients with PJK at three time intervals after surgery (preoperative, immediately after surgery, three months after surgery, and at the last follow-up) is shown in Fig. 5.

Preoperatively, PJK and non-PJK patients did not show particular differences preoperatively. The average preoperative C3–C7 lordosis was similar between the PJK group (12.1° ± 8.3°) and the non-PJK group (17.3° ± 6.2°, $p = .2$). Postoperatively, the cervical lordosis increased by 6.1° in PJK group and 4.7° in non-PJK group, whereas thoracic T1–T12 kyphosis increased by 8.8° ± 6.1° and 9.8° ± 7.2° in the two groups, respectively. The average preoperative T4–T12 kyphosis in the PJK group was 30.6° ± 12.6° and

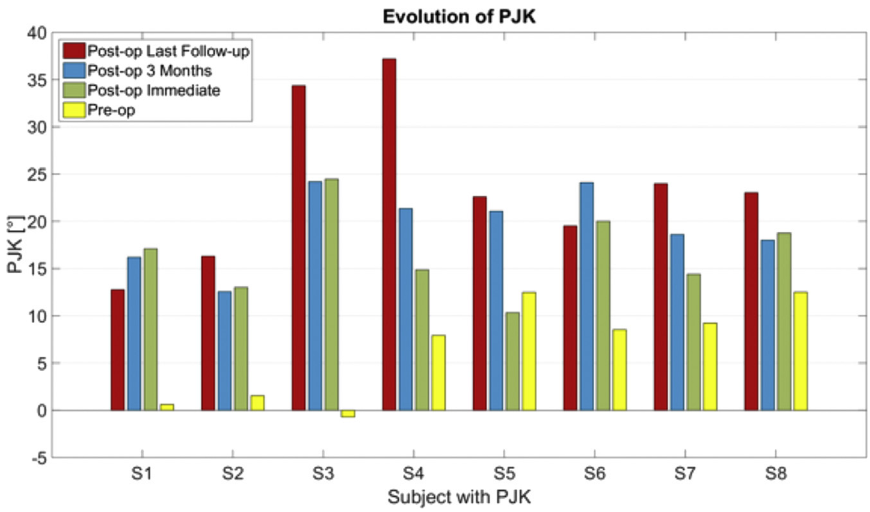

Fig. 5. Evolution of the change in proximal junctional angle among the eight patients with proximal junctional kyphosis (PJK) at three time intervals after surgery.

22.1° ± 11.6° in the non-PJK group (p = .4). The average preoperative L1−S1 lordosis in the PJK group was −57.8° ± 8.9° and −54.9° ± 9.9° in the non-PJK group (p = .4). The average preoperative body inclination in the PJK group was 10° ± 9.9° and −0.6° ± 21.3° in the non-PJK group (p = .5). There was no statistical difference between the mean of UIV-OD and UIV-CCOM offsets among the PJK and non-PJK groups pre- or postoperatively.

Fig. 6 shows an example of a patient who developed a PJK. She had 10° PJK increase from pre- to postoperation, with an increase of almost 20° in T1−T12 kyphosis (from 26° to 45°). Still, she had a preoperative CCOM-HA angle of 0.8° that remained unchanged postoperation. Also, her OD-HA angle only changed from 0.5° preoperation to −0.3° postoperation.

Discussion

The ‘‘cone of economy’’ is a concept that was described by Dubousset: maintaining the head over the pelvis allows for an energy economic status for ambulation and upright posture [20] in which minimum muscular energy is

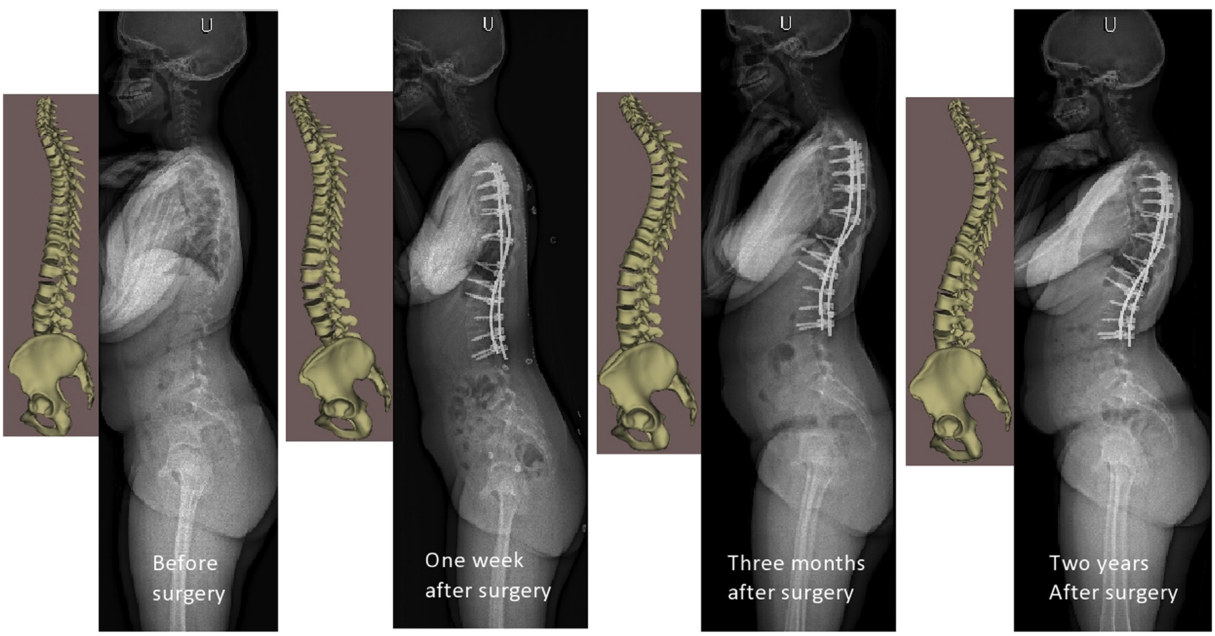

Fig. 6. The evolution of a patient with adolescent idiopathic scoliosis before and after surgery. To keep the head above the pelvis, the patient changes his cervical sagittal alignment and his pelvis shape by increasing the pelvic incidence.

required to maintain balance between the heavy cephalic vertebrae (the head) and the polygon of support (both feet). The predominant role of the pelvis (pelvic vertebrae) is to adapt this posture. Vital et al. conducted an experimental study in six cadavers to determine the center of gravity of the head. Radiologically, this center lies above and slightly in front of the external auditory meatus at the middle of the nasion-inion line. In profile, the axis of gravity passes in front of the cervical spine [5]. El Fegoun et al. conducted an experimental study among normal and scoliotic patients by performing radiographic and force plate analyses. The mean sagittal plane alignment of the gravity in relation to the C7 plumb line revealed an offset anteriorly [21]. To improve surgical treatment, a complete understanding of the deformity and its influence on cervical sagittal alignment seems necessary to optimize correction strategies. Few studies have analyzed sagittal cervical profile in AIS patients [6-9,22,23]. Most authors do not take into consideration the center of gravity of the head. Studying the postural alignment from head to feet allows for a complete view of the possible compensatory mechanisms. Few studies include in their analysis a point at the head level (cranial center of mass) or C2 in normal individuals [24,25]. To our knowledge, no study performed in patients with adolescent idiopathic scoliosis has included a point at the head to analyze global sagittal alignment.

Rousseau et al. reported that the reproducibility of the EOS stereoradiography system is favorably compared with other imaging methods [26]. Also, Ilharreborde et al. has reported that the 3D postoperative reconstructions are as reproducible as preoperative ones and the reproducibility is not influenced by the type of implant used for correction [27]. The small sample size of patients with PJK limits the statistical analysis. Furthermore, it is challenging to achieve a satisfactory posture of the patient while acquiring biplanar radiographic data. This could have influenced the results particularly at the cervical spine level. To limit the effect, every patient was asked to look in a mirror fixed at eye level during data acquisition.

Comparing with normal asymptomatic adolescents, we noticed that the OD-HA angle was almost constant (−2.3°) among the control, non-PJK, and PJK groups with an SD at 2°, 1.9°, and 1.7°, respectively. Six patients had abnormal OD-HA angles postoperatively. Two of them had an OD-HA angle > 1.7° and four had an OD-HA angle < −6.3°. The average CCOM-HA angles in the non-PJK and PJK group were, respectively, −1.3° (SD = 1.8°) and −0.8° (SD = 1.8°) preoperatively and −1.8° (SD = 1.7°) and −2.2° (SD = 1.8°) at the two-year follow-up. The CCOM-HA angle is more relevant to global alignment with less mean and slightly lower SD. It remains almost constant among all patients before and after surgery. The average C7 SVA in normal subjects, non-PJK, and PJK group was −8.9° (SD = 21.6°), −23.2° (SD = 15.7°), and −20.3° (22.7°), respectively, which reveals a posterior shift of the plumb line among the patients with AIS (Table 2).

Sugrue et al. studied 78 asymptomatic 20- to 40-year-old adults and reported the average CCOM-Sacrum offset at 9.0 mm (SD, 31.5 mm) [25]. In our series, we noticed the normal value of CCOM-Sacrum offset among 51 asymptomatic adolescents at −0.74 mm (SD = 17.7 mm). McClendon et al. conducted a study in patients with adult spine deformity with mean age of 60.5 years. The average preoperative CCOM-Sacrum offset was 10.0 cm (SD = 6.58 cm) and the average CCOM-Sacrum offset at the two-year follow-up was 4.19 cm (SD = 4.65 cm). They reported that SRS-22 appearance worsened as preoperative CCOM-Sacrum offset increased ($p < .05$), 2-year SRS-22 appearance and mental health worsened as the 2-year CCOM-Sacrum offset increased ($p < .05$) [28].

Patients tended to keep the head above the pelvis, thus maintaining OD-HA and CCOM-HA within the normal range. Postsurgery compensation mechanism could be an increase or decrease of pelvic incidence, PJK angle, or cervical lordosis,

Table 2
Pre-operative radiological parameters of PJK and non PJK group comparing with normal subjects.

	Mean ± SD (control group)	Mean ± SD (AIS non-PJK group)	Mean ± SD (AIS PJK group)	p value (control, PJK, non-PJK) Kruskal-Wallis test
Pelvic incidence	49.7° (±11.4°)	51° (±9.0°)	49.1° (±9.5)	>.05
Sacral slope	40° (±9.4°)	40.3° (±6.5°)	40.7° (±5.3°)	>.05
Pelvic tilt	9.6° (±7.6°)	10.5° (±6.8°)	9° (±7.5°)	>.05
C7 SVA, mm	−8.9 (±21.6)	−23.2 (±17.3)	−20.3 (±22.7)	**<.05**
C3−C7 lordosis	−3.7° (±0.1°)	17.3° (±6.2°)	12.1° (±8.3°)	**<.05**
T1−T12 kyphosis	42.4° (±12.6°)	31.3° (±10.7°)	38° (±9.6°)	**<.05**
T4−T12 kyphosis	30.2° (±10.6°)	22.1° (±11.6°)	30.6° (±12.6°)	**<.05**
L1−L5 lordosis	−52.1° (±12°)	−54.9° (±9.9°)	−57.8° (±8.9°)	>.05
Inclination angle	−2.8° (±2.7°)	−0.6° (±21.3°)	10° (±9.9°)	**<.05**
OD-HA	−2.3° (±2.0°)	−2.3° (±1.9°)	−2° (±1.7°)	>.05
CCOM-HA	−1.5 (±1.8°)	−1.3° (±1.8°)	−0.8° (±1.8°)	>.05

AIS, adolescent idiopathic scoliosis; CCOM, cranial center of mass; HA, the center of the bi-coxofemoral segment; OD, the most superior point of dentiform apophyse of C2; PJK, proximal junctional kyphosis; SD, standard deviation; SVA, sagittal vertebral axis.

The preoperative thoracic kyphosis (T4−T12) was almost the same among the control and PJK group, 30.2° and 30.6°, respectively, but was less in non-PJK group, 22.1°.

but not at the free spine segment below the instrumentation. Nineteen (22.4%) patients had changed their pelvic incidence more than 5° at the two-year follow-up; 11 patients had increased their pelvic incidence by 8.8° (SD = 2.4°) and 8 patients had decreased their pelvic incidence by 9.6° (SD = 3.7°). Skalli et al. reported the importance of pelvic compensation in posture and motion after posterior spinal fusion and instrumentation for idiopathic scoliosis [29]. Nevertheless, changes in pelvic tilt remain important postoperatively, with 27% of patients showing changes of more than 5°.

At the two-year follow-up, nine patients had a PJK angle between 10° and 15° and two patients had a PJK angle between 30° and 35°. These patients had a clear tendency to decrease their thoracic kyphosis with time at the instrumented level. Comparing with the non-PJK group, the average preoperative thoracic kyphosis (T4−T12) increased by 8.5°. Lonner et al. studied with multivariate analysis the preoperative predisposing factors to maintain the thoracic kyphosis at a two-year follow-up. They reported that greater numbers of levels fused ($r = -0.33$, $p < .001$), preoperative kyphosis ($r = -0.39$, $p < .001$), percentage of screws in the construct ($r = -0.18$, $p = .03$), using standard stainless-steel rods ($r = -0.47$, $p = .011$), and percentage decrease in thoracic curve ($r = -0.23$, $p < .001$) all were correlated with hypokyphosis at follow-up. In one patient, the CCOM-HA angle remain abnormal ($< -4.8°$) after surgery. The CCOM-UIV increased with time after surgery.

C7-HA significantly changed postoperatively, indicating a variation of cervical alignment. However, the head alignment (OD-HA, CCOM-HA) remained quasi-unchanged, as the head was kept above the pelvis, and this irrespectively of other global sagittal alignment, including those parameters, such as pelvic incidence, which are often assumed to be constant.

It is always difficult to demonstrate causality, and therefore it cannot be positively concluded that PJK is a direct cause of changes in sagittal alignment aiming at keeping the head above the pelvis. However, thoracic kyphosis was changed on purpose by surgery for all patients, so it stands to reason that some other aspects of the alignment must have changed to keep OD-HA and CCOM-HA constant. This is what was called a ‘‘compensation mechanism’’ in the present work. Although PJK remains a multifactorial problem, these results suggest that global sagittal alignment could play a role in its development, and therefore analysis of sagittal balance, including the head, should be included in preoperative planning and in the assessment of postoperative results.

Key points

- OD-HA and CCOM-HA angles remain almost constant among the healthy group and the patients, pre- and postoperatively, whether PJK or non-PJK. These two parameters are relevant to global alignment, with CCOM-HA having the lowest average.
- The compensation in AIS patients may occur either at the cervical spine, pelvic incidence, pelvic tilt or at the PJK angle to keep the head above their pelvis.
- The case-by-case analysis showed that adjusting the thoracic kyphosis and the compensations needed to maintain this constant could provide explanatory elements.

References

[1] Lonner BS, Lazar-Antman MA, Sponseller PD, et al. Multivariate analysis of factors associated with kyphosis maintenance in adolescent idiopathic scoliosis. *Spine* 2012;37(15):1297−302.
[2] Yan C, Li Y, Yu Z. Prevalence and consequences of the proximal junctional kyphosis after spinal deformity surgery: a meta-analysis. *Medicine (Baltimore)* 2016;95:e3471.
[3] Kim YJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adolescent idiopathic scoliosis following segmental posterior spinal instrumentation and fusion: minimum 5-year follow-up. *Spine* 2005;30:2045−50.
[4] Kim YJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis in adolescent idiopathic scoliosis after 3 different types of posterior segmental spinal instrumentation and fusions: incidence and risk factor analysis of 410 cases. *Spine* 2007;32:2731−8.
[5] Vital JM, Senegas J. Anatomical bases of the study of the constraints to which the cervical spine is subject in the sagittal plane: a study of the center of gravity of the head. *Surg Radiol Anat* 1986;8:169−73.
[6] Ilharreborde B, Vidal C, Skalli W, Mazda K. Sagittal alignment of the cervical spine in adolescent idiopathic scoliosis treated by posteromedial translation. *Eur Spine J* 2013;22:330−7.
[7] Wang L, Liu X. Cervical sagittal alignment in adolescent idiopathic scoliosis patients (Lenke type 1-6). *J Orthop Sci* 2017;22:254−9.
[8] Norheim EP, Carreon LY, Sucato DJ, et al. Cervical spine compensation in adolescent idiopathic scoliosis. *Spine Deform* 2015;3:327−31.
[9] Hayashi K, Toyoda H, Terai H, et al. Cervical lordotic alignment following posterior spinal fusion for adolescent idiopathic scoliosis: reciprocal changes and risk factors for malalignment. *J Neurosurg Pediatr* 2017;19:440−7.
[10] Youn MS, Shin JK, Goh TS, et al. Relationship between cervical sagittal alignment and health-related quality of life in adolescent idiopathic scoliosis. *Eur Spine J* 2016;25:3114−9.
[11] Protopsaltis TS, Scheer JK, Terran JS, et al. How the neck affects the back: changes in regional cervical sagittal alignment correlate to HRQOL improvement in adult thoracolumbar deformity patients at 2-year follow-up. *J Neurosurg Spine* 2015;23:153−8.
[12] Bridwell KH, Betz R, Capelli AM, et al. Sagittal plane analysis in idiopathic scoliosis patients treated with Cotrel-Dubousset instrumentation. *Spine* 1990;15:644−9.
[13] Labelle H, Dansereau J, Bellefleur C, et al. Comparison between preoperative and postoperative three-dimensional reconstructions of idiopathic scoliosis with the Cotrel-Dubousset procedure. *Spine* 1995;20:2487−92.
[14] Qiu Y, Zhu F, Wang B, et al. Comparison of surgical outcomes of Lenke type 1 idiopathic scoliosis: vertebral coplanar alignment versus derotation technique. *J Spinal Disord Tech* 2011;24:492−9.
[15] Dubousset J, Charpak G, Skalli W, et al. EOS stereo-radiography system: whole-body simultaneous anteroposterior and lateral radiographs with very low radiation dose [in French]. *Rev Chir Orthop Reparatrice Appar Mot* 2007;93(6 suppl):141−3.
[16] Faro FD, Marks MC, Pawelek J, Newton PO. Evaluation of a functional position for lateral radiograph acquisition in adolescent idiopathic scoliosis. *Spine* 2004;29:2284−9.
[17] Dubousset J, Charpak G, Dorion I, et al. A new 2D and 3D imaging approach to musculoskeletal physiology and pathology with low-dose radiation and the standing position: the EOS system [in French]. *Bull Acad Natl Med* 2005;189:287−97; discussion 297−300.

[18] Humbert L, De Guise JA, Aubert B, et al. 3D reconstruction of the spine from biplanar X-rays using parametric models based on transversal and longitudinal inferences. *Med Eng Phys* 2009;31:681−7.

[19] Vialle R, Levassor N, Rillardon L, et al. Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. *J Bone Joint Surg Am* 2005;87:260−7.

[20] Dubousset J. Reflections of an orthopaedic surgeon on patient care and research into the condition of scoliosis. *J Pediatr Orthop* 2011;31(1 suppl):S1−8.

[21] El Fegoun AB, Schwab F, Gamez L, et al. Center of gravity and radiographic posture analysis: a preliminary review of adult volunteers and adult patients affected by scoliosis. *Spine* 2005;30:1535−40.

[22] Yu M, Silvestre C, Mouton T, et al. Analysis of the cervical spine sagittal alignment in young idiopathic scoliosis: a morphological classification of 120 cases. *Eur Spine J* 2013;22:2372−81.

[23] Charles YP, Sfeir G, Matter-Parrat V, et al. Cervical sagittal alignment in idiopathic scoliosis treated by posterior instrumentation and in situ bending. *Spine* 2015;40:E419−27.

[24] Amabile C, Pillet H, Lafage V, et al. A new quasi-invariant parameter characterizing the postural alignment of young asymptomatic adults. *Eur Spine J* 2016;25:3666−74.

[25] Sugrue PA, McClendon J, Smith TR, et al. Redefining global spinal balance: normative values of cranial center of mass from a prospective cohort of asymptomatic individuals. *Spine* 2013;38:484−9.

[26] Rousseau MA, Laporte S, Chavary-Bernier E, et al. Reproducibility of measuring the shape and three-dimensional position of cervical vertebrae in upright position using the EOS stereoradiography system. *Spine* 2007;32:2569−72.

[27] Ilharreborde B, Steffen JS, Nectoux E, et al. Angle measurement reproducibility using EOS three-dimensional reconstructions in adolescent idiopathic scoliosis treated by posterior instrumentation. *Spine* 2011;36:E1306−13.

[28] McClendon J, Graham RB, Sugrue PA, et al. Cranial center of mass compared to C7 plumb line alignment in adult spinal deformity. *World Neurosurg* 2016;91:199−204.

[29] Skalli W, Zeller RD, Miladi L, et al. Importance of pelvic compensation in posture and motion after posterior spinal fusion using CD instrumentation for idiopathic scoliosis. *Spine* 2006;31:E359−66.