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Sex-dependent evolution of whole-body postural alignment with age

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Abstract

Purpose The goal of this study was to explore sex-related variations of global alignment parameters and their distinct evolution patterns across age groups.

Methods This multicentric retrospective study included healthy volunteers with full-body biplanar radiographs in free-standing position. All radiographic data were collected from 3D reconstructions: global and lower limb parameters, pelvic incidence (PI) and sacral slope (SS). Lumbar lordosis (LL), thoracic kyphosis (TK) and cervical lordosis (CL) were also assessed as well as the lumbar and thoracic apex, and thoracolumbar inflexion point. The population was divided into five 5 age groups: Children, Adolescents, Young, Middle-Aged and Seniors.

Results This study included 861 subjects (53% females) with a mean age of 34 ± 17 years. Mean PI was 49.6 ± 11.1 and mean LL was −57.1 ± 11.6°. Females demonstrated a PI increase between Young and Middle-Aged groups (49 ± 11° vs. 55 ± 12°, $p < 0.001$) while it remained stable in males. SS and LL increased with age in females while remaining constant in males between Children and Middle-aged and then significantly decreased for both sexes between Middle-Aged and Seniors. On average, lumbar apex, inflexion point, and thoracic apex were located one vertebra higher in females ($p < 0.001$). After skeletal maturity, males had greater TK than females (64 ± 11° vs. 60 ± 12°, $p = 0.04$), with significantly larger CL (-13 ± 10° vs. -8 ± 10°, $p = 0.03$). All global spinal parameters indicated more anterior alignment in males.

Conclusion Males present more anteriorly tilted spine with age mainly explained by a PI increase in females between Young and Middle-Aged, which may be attributed to childbirth. Consequently, SS and LL increased before decreasing at senior age.

Keywords Sagittal alignment · Age · Sex · Pelvic incidence · Lumbar lordosis · Thoracic kyphosis

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Introduction

The assessment of postural alignment is essential when spinal fusion is considered, particularly in the setting of adult spinal deformity (ASD) correction. Indeed, postoperative malalignment after ASD correction was proven to be correlated with poorer clinical outcomes based on health-related quality of life scores [1]. Patients lose flexibility in the fused segments and consequently lose their ability to recruit spinal compensatory mechanisms to maintain a balanced standing posture [2]. Further, failure to restore physiological spinal curvatures and global alignment after extensive spinal fusion is associated with an increased risk of mechanical complications [3]. These complications are unfortunately relatively frequent, with rates estimated between 30 and 60% in literature [4]. They encompass mainly two types: nonunions and proximal junctional failures. Certain scores have been published to help surgeons identify high-risk patients and decrease mechanical complication rates after ASD surgery, taking into account spinopelvic parameters and age [5].

Pelvic parameters are commonly used to determine optimal spinal curvatures and hence define correction goal [6]. However, thoracic and cervical curvatures cannot be predicted only based on pelvic parameters [7, 8]. Other factors were described to have an influence on spinal curves and global alignment, such as age and sex. Thus, age has been proven to alter global alignment towards an anterior tilt of the spine due to multiple degenerative phenomena [9]. Regarding sex-related variations, greater lumbar lordosis, sacral slope and pelvic incidence were described in females, while males presented greater cervical lordosis and more anterior global alignment [9, 10]. However, studies mainly focused on the effect of either age or sex on spino-pelvic alignment, separately [11]. Thus, it appeared relevant to seek to identify distinct patterns of aging between the sexes regarding global alignment, implementing the analysis with lower limb assessment.

The goal of this study was to investigate sex-related variations of global alignment parameters and their evolution with age using full-body stereoradiography in a large cohort of healthy volunteers.

Methods

Population

This multicentric study included healthy volunteers from previous studies [12–15], as well as newly enrolled subjects. Volunteers presented no major pain in the spine, hip or knee. Exclusion criteria were: any musculoskeletal deformity, scoliosis with a Cobb angle > 15°, isthmic or degenerative spondylolisthesis, history of spinal surgery, and hip or knee replacement. All participants had a full-body biplanar radiograph (EOS™ system, Alphatec, CA, USA) in free-standing position (in upright position, fingers positioned on the cheeks or clavicles, and one foot slightly forward) [16]. This study was approved by regional ethics committees (approval N° 6001 and 6061 C.P.P. Ile-de France VI and FM 312 ethical committee at the Saint-Joseph University, Beirut). All participants provided their informed written consent (or parents' if minor subject).

Parameters

Age, sex, height, weight and body mass index (BMI) were analyzed. Spinopelvic and lower limb three-dimension reconstructions were performed by a specifically trained physician, according to previously validated semi-automated methods [17, 18], which demonstrated good reproducibility [19, 20]. First the spinal line from C3 to L5 was drawn by the user on the frontal and lateral views. The software then generated a 3D spine reconstruction and retro-projected the 3D models of the vertebra on the radiographs. This model was then manually adjusted by the user to precisely fit vertebral contours visible on the radiographs. Similarly, the 3D models of the pelvis and lower limbs were carried out. Last, the odontoid tip was marked.

All following radiographic data were automatically computed based on the skeletal 3D reconstructions:

- *Global spinal alignment parameters*: Sagittal vertical axis (SVA), T1 pelvic angle (TPA), spino-sacral angle (SSA), T1 spino-pelvic inclination (T1SPi) and sagittal odontoid-hip axis angle (ODHA) [21].
- *Spinal parameters*: Lumbar lordosis (LL) was measured from the upper endplate of L1 to the S1 plateau, distal LL (LLdist) from the upper endplate of L4 to the S1 plateau, and proximal LL (LLprox) from the upper endplate of L1 to the upper endplate of L4.

  Thoracic kyphosis (TK) was measured from T1 upper endplate to T12 lower endplate. Proximal TK (TKprox) was defined as the angle between T1 and T5 upper endplates, middle TK (TKmid) between T5 and T9 upper endplates, and distal TK (TKdist) between T9 and L1 upper endplates [22]. This distinction was performed to account for each segment, as they may vary differently [23].

  Cervical lordosis (CL) was measured between C3 and T1 upper endplates, including two components: distal CL (CLdist) from C6 upper endplate to T1 upper endplate and proximal CL (CLprox) from C3 upper endplate to C6 upper endplate. This distinction was performed to account for each segment as they may vary differently [24].

- *Pelvic parameters*: pelvic incidence (PI), pelvic tilt (PT) and sacral slope (SS) [6].
- *Lower limb parameters*: Sacro-femoral angle (SFA), Knee flexion angle (KFA), Ankle flexion angle (AFA) and Pelvic shift (PSh) [25]. These parameters result from the mean of left and right lower limbs values.

Statistical analysis

All variables were tested for normality using Shapiro-Wilk's test. First, a global description of the cohort was made, with parameters expressed by their means ± standard deviations (SD). Sex analysis compared alignment parameters using Student's t tests for normally-distributed variables, and Wilcoxon's otherwise.

The study population was then divided into five groups according to age, with two growing skeleton groups: "Children" (< 12 years) and "Adolescents" (13–19 years), and three mature skeleton groups: "Young" (20–34 years), "Middle-aged" (35–59 years) and "Seniors" (> 60 years). Overall differences of radiographic parameters among PI subsets were assessed using ANOVAs for normally-distributed variables or Kruskal-Wallis tests otherwise. Pairwise Student or Wilcoxon tests with Bonferroni correction were performed to determine significant difference between each age group. To ascertain the relationship between age and alignment parameters by taking into account body mass index, partial correlations controlling for BMI were performed for both sex groups.

By convention, lordotic alignment was expressed by negative values. All statistical analyses were carried out using RStudio (version 1.2.1578), with p-values lower than 0.05 considered significant. Post-hoc power analyses were performed in each age subset using G*Power (version 3.1.9.6).

Table 1 Cohort sample size detailed for each sex and age group. Body mass index values are provided by their means ± 1 standard deviation

	Males	Females	Total
Children (≤ 12 years)	$N=18$ BMI = 15.6 ± 0.7	$N=69$ BMI = 15.4 ± 3.2	87
Adolescents (13–19 years)	$N=32$ BMI = 21.1 ± 3.8	$N=31$ BMI = 17.8 ± 2.4	63
Young (20–34 years)	$N=207$ BMI = 23.8 ± 3.0	$N=179$ BMI = 22.2 ± 4.1	386
Middle-Aged (35–59 years)	$N=94$ BMI = 26.1 ± 3.2	$N=125$ BMI = 25.7 ± 5.3	219
Seniors (≥ 60 years)	$N=51$ BMI = 26.0 ± 2.9	$N=55$ BMI = 26.2 ± 6.4	106
Total	402	459	861

Results

Cohort description

The cohort included 861 healthy subjects, aged from 4 to 90 years (mean = 34, SD = 17.7). There were 53.3% of females. The cohort sample size by age group and sex is provided in Table 1. Mean PI was 49.8 ± 11.°1, mean LL was − 57.1 ± 11.4°, mean TK was 53.2 ± 11.4° and mean CL was − 4.8 ± 11.8°. BMI (data was available for 610 subjects) increased along with age groups except between Middle-aged and Seniors (Table 1).

Lumbar apex *($p = 0.003$)*, thoraco-lumbar inflexion point *($p < 0.001$)* and thoracic apex *($p < 0.001$)* were located significantly more cephalad in female subjects (Fig. 1). Inflexion point was mainly located in L1 in males (40.5%), and in T12 for 37.1% of females. Thoracic apex was most frequently located in T7 in males (37.6%) while it was in T6 in women (38.1%).

All global spinal alignment parameters indicated more anterior global alignment in males while females presented more dorsally inclined spines. ODHA, SSA, SVA and T1SPi values were significantly different between sexes after skeletal maturity (Table 2).

Sex-related variations according to age

PI increased during growth in both sexes, then remained stable in males whereas it further increased between "Young" and "Middle-aged" groups in females (49.3 ± 11.3° versus 54.6 ± 12.3°, $p < 0.001$) (Table 3). Pelvic tilt increased constantly with age in both sexes (Table 3). Sacral slope evolution with age varied differently between sexes with age (Table 3): in males, SS remained stable and then decreased significantly between "Middle-aged" and "Seniors" (38.4 ± 8.0° versus 31.5 ± 8.8°, $p < 0.001$). In females, SS increased with maturation until middle age, and then significantly diminished (41.0 ± 8.8° versus 35.4 ± 7.8°, $p < 0.001$). In the two older groups, SS was higher in females.

LL varied in the same way as SS between age and sex groups, with greater lordosis (through its proximal component) in females after skeletal maturity (Fig. 2). LL significantly increased in females between Adolescent and Young groups ($p = 0.02$). Thoracic kyphosis constantly increased with age in both sexes through proximal and middle segments (Table 4). Distal TK exhibited little variation with age and sex. In males, TKmax and TKprox became greater than those in females after skeletal maturity. In every age group, males presented greater cervical lordosis than female subjects. This difference was mainly located in proximal CL with significant divergence between sexes, while distal CL exhibited little variation (Table 5). On average, female

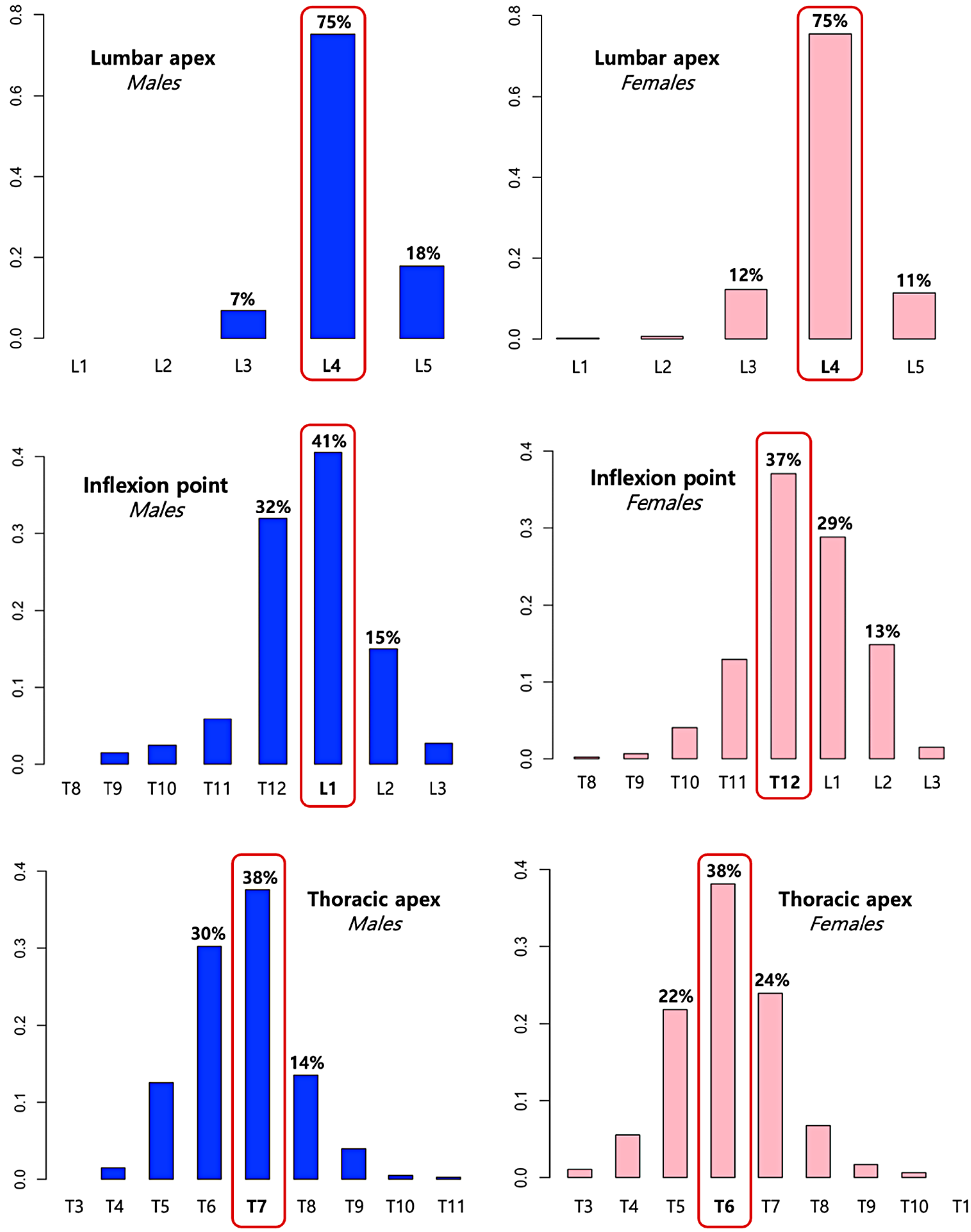


Fig. 1 Barplot representation of lumbar apex, thoraco-lumbar inflexion point and thoracic apex according to sex. Most frequent vertebra is circled in red and written in bold

proximal cervical spines were kyphotic in all age groups except Seniors.

In both sexes, TPA, SVA and SSA indicated more anterior spine tilt in older groups, while T1SPi remained stable with age (Table 2). SFA values constantly increased with age, similarly in males and females (Fig. 3). In both sexes, knee flexion angle remained stable with age, ranging between 4.1 and 5.5° in males, and 4.2 and 6.6° in females while ankle flexion tended to increase with age, with a significant variation in Seniors (Fig. 3).

Partial correlations controlling for BMI confirmed the significant effect of age on global alignment, lower limb parameters, TK and cervical lordosis (Table 6). In males, LL and LLprox were correlated with age unlike in females.

Discussion

Knowing and predicting the evolution of spinal alignment appears relevant as the ASD correction surgery is performed at a given time and must stand the test of time and the physiological alterations of alignment with aging. To our knowledge, this is the first study analyzing sex- and age-related variations of whole-body alignment on stereoradiography in a large cohort of healthy volunteers. Indeed, previous studies did not analyze whole body [11] or with small sample size [26]. The results showed that the alignment differences between sexes evolved differently with age, after taking into account the effect of BMI. Males presented a more anterior spinal alignment, with a lower LL and greater TK,

Table 2 Global alignment parameters comparison according to sex in the five age subsets. Statistically significant p-values are marked with a "*". Values are expressed by their means ± 1 standard deviation

Global alignment parameters	Males	Females	*p*-value
ODHA *(°)*			
Children *(≤ 12)*	-1.7 ± 2.7	-3.0 ± 2.1	*0.23*
Adolescents *(13–19)*	-1.1 ± 2.2	-2.5 ± 2.0	*0.01**
Young *(20–34)*	-1.9 ± 2.2	-3.3 ± 1.8	*< 0.001**
Middle-aged *(35–59)*	-1.9 ± 2.2	-3.5 ± 2.2	*< 0.001**
Seniors *(≥ 60)*	0.5 ± 3.3	-2.4 ± 3.0	*< 0.001**
p-value	*< 0.001**	*0.004**	-
TPA *(°)*			
Children *(≤ 12)*	-0.5 ± 5.3	-0.8 ± 7.5	*0.67*
Adolescents *(13–19)*	4.1 ± 5.2	2.5 ± 5.7	*0.13*
Young *(20–34)*	6.0 ± 6.0	2.8 ± 7.2	*< 0.001**
Middle-aged *(35–59)*	7.4 ± 6.3	6.9 ± 6.9	*0.28*
Seniors *(≥ 60)*	13.0 ± 7.7	11.5 ± 6.7	*0.33*
p-value	*< 0.001**	*< 0.001**	-
SSA *(°)*			
Children *(≤ 12)*	132.6 ± 9.5	131.5 ± 6.9	*0.67*
Adolescents *(13–19)*	130.9 ± 7.6	131.6 ± 6.9	*0.83*
Young *(20–34)*	131.8 ± 7.0	134.8 ± 9.1	*< 0.001**
Middle-aged *(35–59)*	130.5 ± 7.7	134.9 ± 8.7	*< 0.001**
Seniors *(≥ 60)*	121.2 ± 9.9	127.3 ± 8.5	*0.002**
p-value	*< 0.001**	*< 0.001**	-
SVA *(mm)*			
Children *(≤ 12)*	-7.9 ± 22.6	-26.5 ± 16.5	*0.004**
Adolescents *(13–19)*	-2.9 ± 20.6	-19.7 ± 13.5	*< 0.001**
Young *(20–34)*	-8.4 ± 20.8	-24.9 ± 19.9	*< 0.001**
Middle-aged *(35–59)*	-5.7 ± 20.6	-18.6 ± 21.0	*< 0.001**
Seniors *(≥ 60)*	17.7 ± 34.5	-1.2 ± 26.2	*0.008**
p-value	*< 0.001**	*< 0.001**	-
T1SPi *(°)*			
Children *(≤ 12)*	-3.8 ± 3.5	-6.4 ± 1.9	*0.01**
Adolescents *(13–19)*	-3.9 ± 2.6	-5.7 ± 2.1	*0.02**
Young *(20–34)*	-5.1 ± 2.1	-6.4 ± 2.2	*< 0.001**
Middle-aged *(35–59)*	-5.2 ± 2.3	-6.7 ± 2.4	*< 0.001**
Seniors *(≥ 60)*	-4.0 ± 3.3	-6.0 ± 3.0	*0.007**
p-value	*0.05*	*0.17*	-

compensated by a greater CL. Thoraco-lumbar alignment moved forward with aging, but global alignment remained balanced with the recruitment of compensatory mechanisms such as cervical extension, pelvic retroversion, hip extension and ankle flexion.

Global alignment parameters indicated more anteriorly tilted spine in males. This finding is in line with Janssen et al.'s conclusions [16]. According to these authors, this phenomenon may indicate less rotational stability in female spine due to higher dorsally directed shear loads, possibly explaining the greater occurrence of thoracic idiopathic scoliosis in girls than boys. In this study, T1SPi, SVA, SSA and ODHA significantly differed between sexes after skeletal maturity. These results are in contrast with Charles et al.'s

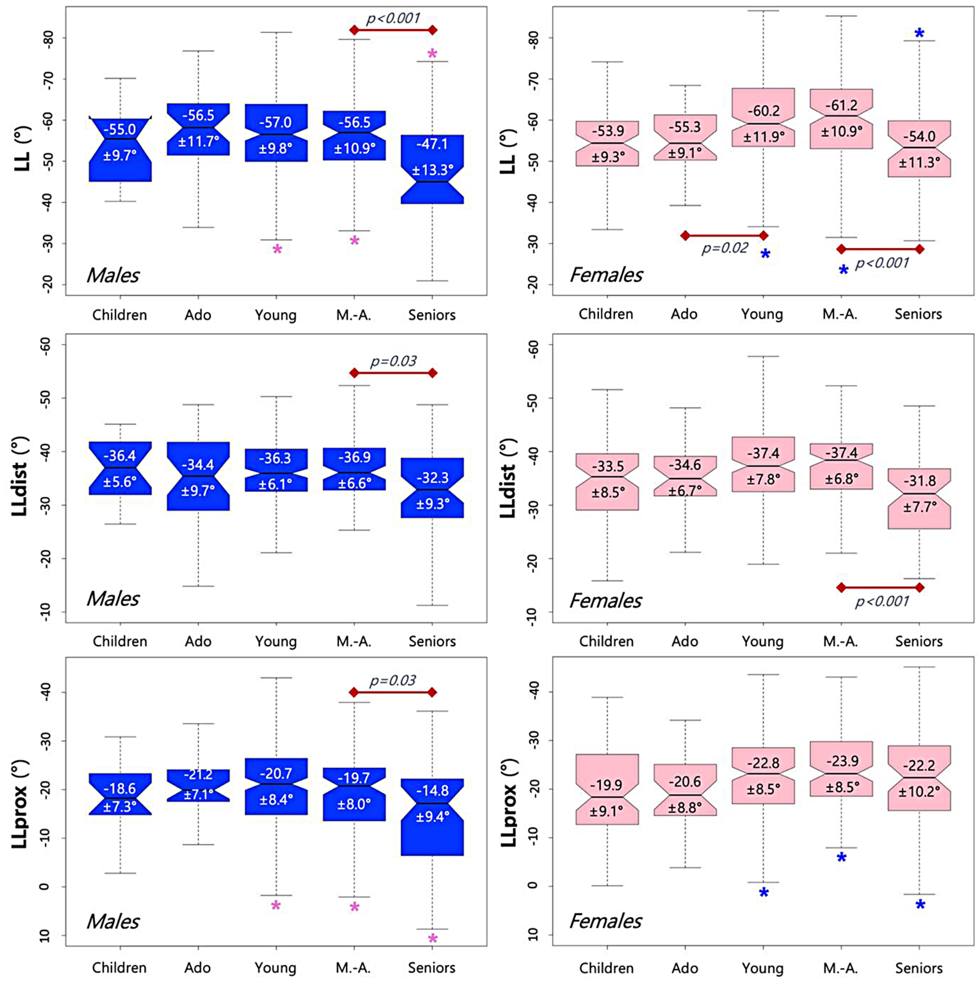
Table 3 Pelvic parameters comparison according to sex in the five age subsets. Statistically significant p-values are marked with a "*". Values are expressed by their means ± 1 standard deviation

Pelvic parameters	Males	Females	*p*-value
Pelvic incidence *(°)*			
Children *(≤ 12)*	43.2 ± 13.2	41.5 ± 9.6	*0.63*
Adolescents *(13–19)*	46.9 ± 7.7	45.5 ± 7.8	*0.37*
Young *(20–34)*	50.5 ± 9.7	49.3 ± 11.3	*0.26*
Middle-aged *(35–59)*	51.1 ± 10.1	54.6 ± 12.3	*0.09*
Seniors *(≥ 60)*	48.5 ± 10.3	52.9 ± 11.4	*0.07*
p-value	*0.01**	*< 0.001**	-
Pelvic tilt *(°)*			
Children *(≤ 12)*	3.3 ± 5.9	5.6 ± 7.7	*0.35*
Adolescents *(13–19)*	8.0 ± 5.9	8.1 ± 6.8	*0.94*
Young *(20–34)*	11.1 ± 6.1	9.2 ± 7.8	*0.01**
Middle-aged *(35–59)*	12.6 ± 6.7	13.6 ± 7.3	*0.71*
Seniors *(≥ 60)*	17.0 ± 7.3	17.5 ± 7.2	*0.88*
p-value	*< 0.001**	*< 0.001**	-
Sacral slope *(°)*			
Children *(≤ 12)*	39.9 ± 10.5	35.9 ± 7.1	*0.08*
Adolescents *(13–19)*	38.9 ± 7.0	37.3 ± 6.7	*0.35*
Young *(20–34)*	39.3 ± 7.0	40.0 ± 8.6	*0.41*
Middle-aged *(35–59)*	38.4 ± 8.0	41.0 ± 8.8	*0.03**
Seniors *(≥ 60)*	31.5 ± 8.8	35.4 ± 7.8	*0.02**
p-value	*< 0.001**	*< 0.001**	-

findings, exhibiting no significant differences in ODHA and SSA between sexes [11]. However, studies from Bassani and Yukawa et al. corroborate SVA being greater in males [9, 27]. In this study, PT, SFA and AFA increased with age in both groups, describing compensatory mechanisms of the pelvis and lower limbs to maintain global alignment as it tends to move forward [2].

The main driver for this global alignment divergence is the greater LL in females. Indeed, this study's results indicated that LL remained stable in males, before a significant decrease at senior age, while LL increased in females until middle-age before declining in the oldest group. Accordingly, thoraco-lumbar inflexion point and thoracic apex were, on average, located one vertebra more cephalad in females than males. This greater LL in females after skeletal maturity can be explained by the concomitant PI increase. Indeed, although PI increased with growth in both sexes and remained stable in mature males, PI significantly increased in females between Young and Middle-Aged groups, by 5°. This phenomenon may be explained by pregnancy in women, leading to anterior rotation of the sacrum with respect to ilium through the sacro-iliac joints. Accordingly, Bailey et al. described spino-pelvic changes with parity, with greater PI-LL mismatch in multiparous women [28]. In parallel to the increase in LL in females, SS increased before declining in Seniors, whereas in males sacral slope remained stable until Middle-Aged group before decreasing

Fig. 2 Boxplot representation of LL, LLprox and LLdist according to sex in every age subset. In the boxes are written means ± standard deviations for each age category. Significant differences between contiguous age groups are denoted with a red segment and associated p-value. Asterisks next to the boxes denote significant difference compared to the other sex. *M.-A. = Middle-Age*



in Seniors. SS was eventually greater in female subjects in the Middle-Aged and Senior groups compared with males. Consistently, Vialle et al. found greater SS in females [10].

The second mechanism explaining more anterior tilt of male spines would be a greater TK. Although similar in children, the greater increase in males led to significantly higher values in all age groups after skeletal maturity. All segments of TK increased with age, with lowest variations exhibited in distal TK, with a 3°-difference between Children and Seniors. This finding is in agreement with Prost et al. describing an invariant segment between T10 and L1, not correlated with PI nor age [29]. Middle TK increased with age in a similar fashion between the two sex groups. However, proximal TK increase was more pronounced in males, leading to significantly higher values after skeletal maturity and explaining the overall TKmax greater increase in males. Accordingly, Ouchida et al. found greater proximal TK in males in a study on 317 subjects [30]. This phenomenon might be explained by the diverging mechanical properties of lungs on thoracic alignment between sexes, as it has been demonstrated that rib cage volume is associated with sex, age and height [31].

Females presented more kyphotic cervical spines than males. While distal cervical curve was lordotic in all age groups in females, proximal cervical curve was kyphotic in all groups except Seniors. As a result, global cervical curvature was kyphotic in skeletally immature females and became lordotic in older groups. In contrast, male cervical spines were overall lordotic in all age groups, in distal and proximal segments. Hence, males presented greater cervical lordosis than females, with increasing values with age. Yukawa et al. found similar results in a study on 626 subjects [27], but Charles et al. exhibited no significant difference in C2-C7 lordosis between males and females [24]. However, our study revealed that this increase in CL mainly occurred in proximal segment as distal CL exhibited little variation with age and sex. This finding suggests that cervical curvature mainly acts as a compensatory mechanism for global postural alignment, rather than its basic anatomical relationship with upper thoracic spine.

The findings of this study are helpful in contouring the rods for adult spinal deformity surgery. Indeed, when treating male patients, the rod should be contoured with less proximal lordosis and more thoracic kyphosis, and the

Table 4 Thoracic kyphosis parameters comparison according to sex in the five age subsets. Statistically significant p-values are marked with a "*". Values are expressed by their means ± 1 standard deviation

Thoracic kyphosis	Males	Females	*p*-value
TK *(°)*			
Children *(≤ 12)*	46.9 ± 11.0	44.1 ± 9.3	*0.28*
Adolescents *(13–19)*	51.3 ± 9.9	45.7 ± 12.8	*0.036**
Young *(20–34)*	54.6 ± 10.6	51.7 ± 11.2	*0.009**
Middle-aged *(35–59)*	56.8 ± 9.6	54.1 ± 9.8	*0.04**
Seniors *(≥ 60)*	61.8 ± 12.1	57.8 ± 12.3	*0.11*
p-value	*< 0.001**	*< 0.001**	-
TKprox *(°)*			
Children *(≤ 12)*	17.8 ± 7.2	16.8 ± 6.2	*0.39*
Adolescents *(13–19)*	15.3 ± 7.3	15.9 ± 7.2	*0.54*
Young *(20–34)*	20.6 ± 7.1	18.6 ± 7.6	*0.007**
Middle-aged *(35–59)*	20.6 ± 9.1	18.1 ± 7.1	*0.02**
Seniors *(≥ 60)*	23.1 ± 9.3	19.3 ± 9.1	*0.03**
p-value	*0.001**	*0.23*	-
TKmid *(°)*			
Children *(≤ 12)*	19.5 ± 5.6	19.1 ± 5.7	*0.77*
Adolescents *(13–19)*	22.9 ± 8.0	19.5 ± 7.0	*0.1*
Young *(20–34)*	23.2 ± 6.7	22.2 ± 7.1	*0.24*
Middle-aged *(35–59)*	23.6 ± 7.6	23.9 ± 6.1	*0.54*
Seniors *(≥ 60)*	26.2 ± 6.3	26.7 ± 8.0	*0.92*
p-value	*0.009**	*< 0.001**	-
TKdist *(°)*			
Children *(≤ 12)*	6.1 ± 5.8	5.0 ± 6.3	*0.38*
Adolescents *(13–19)*	9.0 ± 7.0	6.8 ± 6.5	*0.17*
Young *(20–34)*	6.8 ± 7.1	7.6 ± 7.0	*0.11*
Middle-aged *(35–59)*	8.4 ± 8.4	7.8 ± 7.6	*0.53*
Seniors *(≥ 60)*	9.1 ± 9.0	7.8 ± 9.0	*0.39*
p-value	*0.23*	*0.05*	-

Table 5 Cervical lordosis parameters comparison according to sex in the five age subsets. Statistically significant p-values are marked with a "*". Values are expressed by their means ± 1 standard deviation

Cervical lordosis	Males	Females	*p*-value
CL *(°)*			
Children *(≤ 12)*	-11.4 ± 17.9	6.3 ± 9.3	*< 0.001**
Adolescents *(13–19)*	-3.8 ± 11.4	5.0 ± 10.5	*0.002**
Young *(20–34)*	-7.9 ± 10.3	-1.6 ± 11.7	*< 0.001**
Middle-aged *(35–59)*	-9.8 ± 11.0	-3.7 ± 8.9	*< 0.001**
Seniors *(≥ 60)*	-12.5 ± 9.9	-8.2 ± 10.3	*0.03**
p-value	*0.004**	*< 0.001**	-
CLprox *(°)*			
Children *(≤ 12)*	-6.7 ± 12.6	6.7 ± 7.0	*< 0.001**
Adolescents *(13–19)*	0.3 ± 13.2	8.8 ± 8.6	*0.006**
Young *(20–34)*	-1.8 ± 8.5	3.0 ± 9.2	*< 0.001**
Middle-aged *(35–59)*	-5.0 ± 10.3	0.6 ± 7.5	*< 0.001**
Seniors *(≥ 60)*	-9.0 ± 8.2	-3.4 ± 8.9	*< 0.001**
p-value	*< 0.001**	*< 0.001**	-
CLdist *(°)*			
Children *(≤ 12)*	-4.8 ± 6.8	-0.3 ± 6.8	*0.04**
Adolescents *(13–19)*	-4.0 ± 5.9	-3.8 ± 5.6	*0.86*
Young *(20–34)*	-6.1 ± 6.5	-4.6 ± 6.6	*0.03**
Middle-aged *(35–59)*	-4.9 ± 7.7	-4.3 ± 6.0	*0.57*
Seniors *(≥ 60)*	-3.5 ± 7.0	-4.8 ± 7.0	*0.36*
p-value	*0.13*	*< 0.001**	-

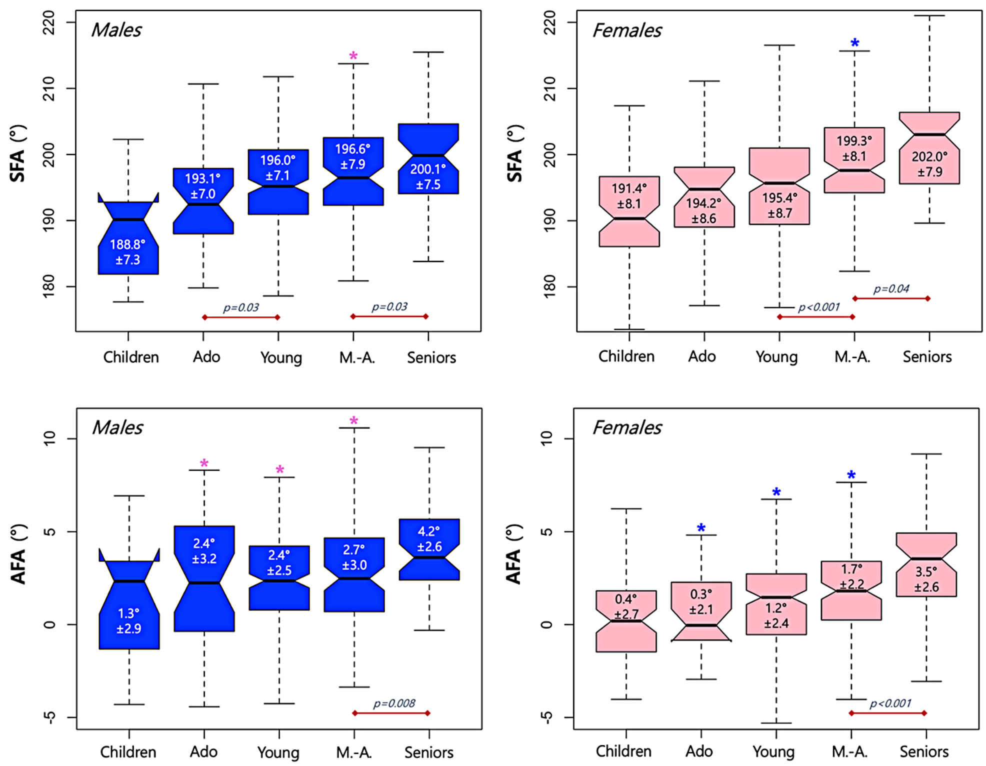


Fig. 3 Boxplot representation of SFA and AFA according to sex in every age subset. In the boxes are written means ± standard deviations for each age category. Significant differences between contiguous age groups are denoted with a red segment and associated p-value. Asterisks in the boxes denote significant difference compared to the other sex. *M.-A.* = *Middle-Age*

Table 6 Partial correlations with age controlling for BMI for each sex. Statistically significant p-values are marked with a "*" and respectively coefficient correlations in bold

Partial correlations	Males (*n* = 402)		Females (*n* = 459)	
Pelvic parameters	r	*p-value*	r	*p-value*
PI *(°)*	0	*0.86*	**0.2**	*0.001**
PT *(°)*	**0.3**	*< 0.001**	**0.3**	*0.001**
SS *(°)*	**-0.2**	*< 0.001**	-0.1	*0.09*
Spinal curvatures				
LL *(°)*	**0.3**	*< 0.001**	0.1	*0.29*
LLprox *(°)*	**0.3**	*< 0.001**	0	*0.42*
LLdist *(°)*	**0.2**	*< 0.001**	**0.1**	*0.02**
TK max *(°)*	**0.2**	*< 0.001**	**0.3**	*< 0.001**
TKprox *(°)*	**0.2**	*0.002**	0	*0.84*
TKmid *(°)*	0	*0.59*	**0.3**	*< 0.001**
TKdist *(°)*	0	*0.70*	0	*0.34*
CL *(°)*	**-0.2**	*< 0.001**	**-0.2**	*< 0.001**
CLprox *(°)*	**-0.3**	*< 0.001**	**-0.2**	*< 0.001**
CLdist *(°)*	0.1	*0.18*	-0.1	*0.06*
Global alignment				
ODHA *(°)*	0.1	*0.20*	0	*0.19*
TPA *(°)*	**0.3**	*< 0.001**	**0.3**	*< 0.001**
SSA *(°)*	**-0.3**	*< 0.001**	**-0.1**	*0.005**
SVA *(mm)*	**0.2**	*0.001**	**0.3**	*0.001**
T1SPi *(°)*	0	*0.48*	0.1	*0.19*
Lower limbs				
PSh *(mm)*	**-0.2**	*< 0.001**	**-0.3**	*< 0.001**
SFA *(°)*	**0.2**	*< 0.001**	**0.2**	*< 0.001**
KFA *(°)*	0	*0.67*	**-0.2**	*< 0.001**
AFA *(°)*	**-0.1**	*0.01**	**-0.3**	*< 0.001**

inflexion point should be aimed at L1, and the thoracic apex at T7. Moreover, it could be relevant to increase lordotic contour in the lumbar spine in the setting of adolescent idiopathic scoliosis surgery, in anticipation of PI and LL increase in women in the following decade. Further studies would be required to ascertain this hypothesis.

Limitations

The first limitation of this study is its cross-sectional feature. A longitudinal study would be required to ascertain the effect of age on alignment, including the variation in pelvic parameters and lumbar lordosis. However, it is complex to set up with a sufficient follow-up of healthy volunteers. A second limitation would be the relatively low sample size in the male children group. This could explain the absence of statistical significance in sacral slope comparison between males and females in children (power = 7% in this group, 8% in adolescents, and above 80% for the other groups). It would have been interesting to analyze pregnancy data in females, to assess its impact on PI increase, it was however not available. Last, BMI data were not available for every volunteer included in this study, and we were not able to assess muscle strength and mass in the trunk and the lower limbs. Despite these limitations, this study provides evidence to adjust alignment goal according to patients' age and sex.

Conclusion

Global alignment varies between sexes, and evolves differently with age, after taking body mass index effect into account. Males presented more anteriorly tilted spines, with lower LL and greater TK, compensated by a greater proximal cervical lordosis. Unlike males, females presented increasing SS and LL with age before declining in Senior group, due to PI increase between Young and Middle-Aged groups. TK increased with age, in a more pronounced fashion in its proximal segment in males. PT, SFA and AFA increased similarly with age in both groups to maintain balance.

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Declarations

conflict of interest The authors have no conflict of interest to declare relativeky to this study.

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