The relative contribution of discs and vertebral bodies to thoracic kyphosis in healthy volunteers

Mikael Finoco[1,2] · Renaud Lafage[2] · Claudio Vergari[3] · Wafa Skalli[3] · Jonathan Elysée[2] · Ayman Assi[4] · Pierre Guigui[1] · Emmanuelle Ferrero[1] · Virginie Lafage[2] · Marc Khalife[1,2]

Abstract

Introduction Understanding the normal anatomy of thoracic kyphosis (TK) in healthy subjects is essential for evaluating sagittal malalignment and planning the surgery accordingly. The aim of this study was to identify the proportion of thoracic kyphosis originating from disc versus vertebral body shape and to describe its variation according to age and thoracic kyphosis magnitude.

Methods This study was a retrospective review of a prospective multicenter database of healthy volunteers aged 18 years or older. Vertebral body and disc sagittal Cobb angles were measured at each level and summed within each of the 3 TK regions (Upper, Middle and Lower TK). Relative contributions of discs and vertebral bodies to Upper, Middle, Lower, and total TK were assessed in the whole cohort, and according to age and TK groups, after stratification. Finally, a multivariate analysis including age and TK magnitude was conducted.

Results Among these 645 subjects, the mean age was 37.6 ± 16.3 years with 51% of females. Intervertebral discs were kyphotic in Upper and Middle TK with respective discs contribution to total TK of 4.2% and 9.6%, for a total of 13.8% of total kyphosis. Lower TK discs were lordotic, with a participation of -13.2% of total TK, leading to an overall discs contribution to TK of 0.6%. Vertebral bodies were all kyphotic with a contribution of 99.4% of total kyphosis. Vertebral bodies kyphosis increased across age groups for Middle TK ($p = 0.004$), Lower TK ($p < 0.001$), and Total TK ($p < 0.001$). Discs contributions to total TK increased significantly with increasing TK (-13.8% for Low TK, -1.5% for Average-Low TK, 5.7% for Average-High TK and 9.1% for High TK), ($p < 0.001$). Finally, discs contribution was significantly greater in males than in females, with respective values of 2.6% and -1.8% ($p = 0.01$).

Conclusion This study highlights the predominant role of vertebral bodies contribution to thoracic kyphosis, 99.4% on average. The contribution of disc to thoracic kyphosis (values ranging from -13.8% to 9.1%) increases significantly with increasing thoracic kyphosis magnitude. The association of age with thoracic kyphosis was greater for vertebral bodies than discs, particularly in Middle and Lower TK.

Keywords Discs versus vertebral bodies; Thoracic kyphosis, Discs contribution; Vertebral bodies contribution; Healthy volunteers, Age

Introduction

The upright erect position and bipedal walking that humans perform daily rely on spino-pelvic balance, and therefore depend on the adequation between pelvic parameters and spinal curvatures [1, 2]. With physiological or pathological aging, this alignment is modified with a decrease in lumbar lordosis and an increase in thoracic kyphosis [3–5]. These changes can trigger spinopelvic compensation mechanisms to maintain a horizontal gaze [6–8]. A thorough understanding of these mechanisms requires first extensive knowledge of normative spinal anatomy.

The loss of lumbar lordosis has been recognized as a major driver of adult spinal deformity and spino-pelvic malalignment [3]. Consequently, lumbar lordosis has been the focus of numerous publications examining its amplitude, distribution, apex, age-related changes, and its relationship with pelvic morphology [9–11]. This body of literature has enhanced our understanding of lumbar lordosis and led to the definition of patient-specific alignment based on pelvic morphology and age [12–14]. In contrast, thoracic kyphosis has not been studied extensively.

Understanding the normal anatomy of thoracic kyphosis (TK) in healthy subjects is essential for evaluating sagittal malalignment and planning the surgery accordingly. Thoracic kyphosis amplitude and apex distribution have recently been studied in the literature [15]. Lafage et al. described the association between the amplitude of thoracic kyphosis and its shape, finding that in subjects with small kyphosis, two-thirds of the curvature was located in the upper segments of the thoracic spine, while in subjects with large kyphosis, the curvature tended to adopt a symmetrical shape around T7 [16]. Other studies have explored correlations between age and TK, as well as the relationship between age, vertebral bodies, and disc height [17]. Finally, He et al. recently studied 32 patients with degenerative thoraco-lumbar deformity, finding that vertebral bodies contributed 94.2% to total curvature, significantly more than the 5.77% contribution from discs [18]. However, the respective contributions of each vertebral body and disc to thoracic kyphosis, as well as their variation according to age or TK magnitude, have not been studied in a healthy population, to our knowledge and still represents a gap in the literature.

Therefore, the aim of this study was to identify the proportion of thoracic kyphosis originating from disc versus vertebral body shape and to describe its variation according to age and thoracic kyphosis magnitude.

Methods

Patient population

This study was a retrospective review of a prospective multicenter database of healthy volunteers aged 18 years or older. All subjects underwent full-body stereoradiography in free-standing position. Subjects with spine pain, previous spine surgery, history of spinal fracture, knee/hip osteoarthritis or replacement were excluded. Subjects with transitional vertebrae in the thoracic or lumbar spine were also not included. This study was conducted after IRB approval (CPP Ile-de-France VI – Approval # 6036). All participants gave their informed consent to participate in this study.

Data collection

Demographic parameters, including age, sex, and body mass index (BMI), were collected. Radiographic parameters were obtained after 3D reconstruction of the spine and pelvis using a previously validated semi-automated method [19, 20], which demonstrated good reproducibility [21, 22]. 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 spinal 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. Upon data extraction, the radiographic parameters of interest for the current analysis included:

- Total thoracic kyphosis (TK): Upper endplate of T1- Upper endplate of L1;
- Lumbar lordosis (LL): Upper endplate of L1- Upper endplate of S1.
- Pelvic incidence (PI).

Total TK was split into 3 equal regions because these 3 regions vary differently [23, 24], (Fig. 1):

- Upper TK (T1 upper endplate - T5 Upper endplate),
- Middle TK (T5 upper endplate - T9 upper endplate),
- Lower TK (T9 upper endplate - L1 upper endplate).

Vertebral body and disc sagittal Cobb angles were measured at each level and summed within each of the 3 TK regions. For each region (upper, middle, and lower TK) and for the total TK, a ratio was calculated between the sum of the discs angles and the regional TK angle (including bone and discs) and another ratio between the sum of the discs angles and the global TK angle (also including bone and discs). The same ratios were calculated for the vertebral bodies. Relative contributions of discs and vertebral bodies to Upper, Middle, Lower, and total TK were assessed.

Statistical analysis

First, demographics and radiographic parameters were described for the whole cohort and expressed as mean ± standard deviation (SD). The normality of variable distribution was tested using the Shapiro-Wilk test. Correlations were sought between age, PI, LL, total TK, and each of the 3 TK regions. Discs and vertebral bodies' contribution to regional and total TK were described for the whole cohort and expressed as median and inter-quartile range (IQR). The cohort was stratified using Jenks method into four age

Fig. 1 Thoracic kyphosis (TK) breakdown into 3 regions: Upper TK (Upper endplate of T1- Upper endplate of T5), Middle TK (Upper endplate of T5- Upper endplate of T9, Lower TK (Upper endplate of T9- Upper endplate of L1) [23]

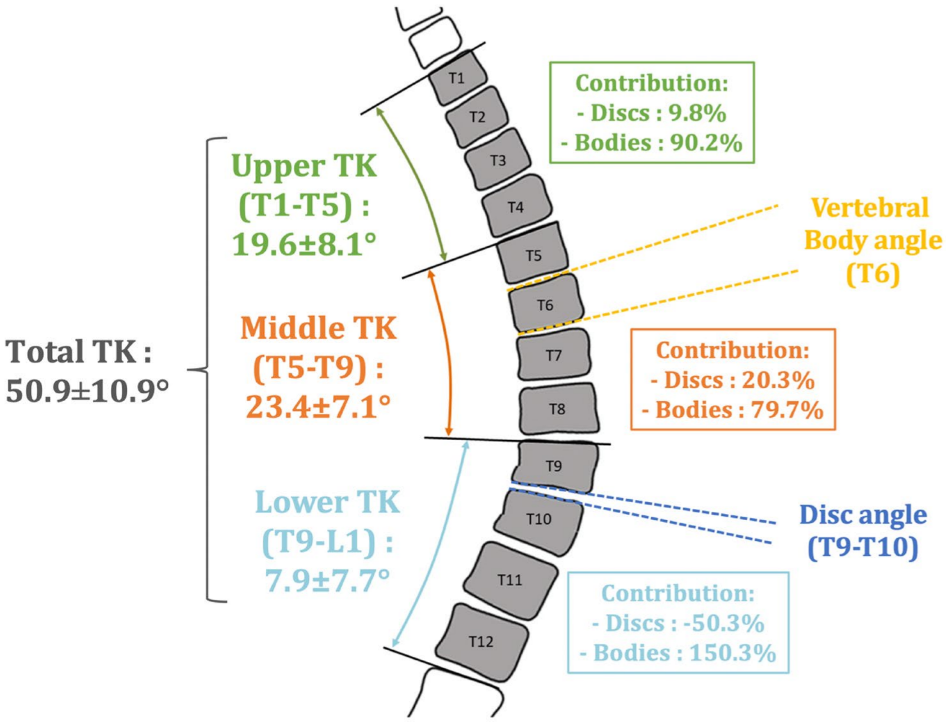

Table 1 Mean ± SD regional kyphosis (expressed in degree) for upper TK, middle TK and lower TK according to age. Significant p-values from ANOVA or Kruskal-Wallis analyses are denoted with an asterisk if < 0.05

Age groups	Cohort (*n* = 645)	Young (*n* = 291)	Adult (*n* = 139)	Middle-aged (*n* = 112)	Older (*n* = 103)	*p*-values
Regional disc angles in thoracic kyphosis (°)						
Upper TK	2.1 ± 6.9	1.9 ± 7.3	2.5 ± 6.3	1.4 ± 6.8	2.8 ± 6.5	*0.31*
Middle TK	4.9 ± 4.5	4.9 ± 4.4	4.4 ± 4.2	4.9 ± 4.2	5.8 ± 5.1	*0.10*
Lower TK	−6.9 ± 5.7	−6.7 ± 5.5	−6.7 ± 5.2	−7.1 ± 6.5	−7.9 ± 6.3	*0.31*
Total Discs	0.02 ± 10.2	0.1 ± 9.9	0.1 ± 9.8	−0.9 ± 11.0	0.7 ± 11.0	*0.72*
Regional vertebral body angles in thoracic kyphosis (°)						
Upper TK	17.5 ± 7.9	17.5 ± 7.8	17.1 ± 7.3	17.4 ± 8.3	18.2 ± 8.3	*0.74*
Middle TK	18.5 ± 5.6	17.9 ± 5.0	18.4 ± 6.1	18.8 ± 5.7	20.3 ± 6.1	***0.004****
Lower TK	14.8 ± 5.7	13.9 ± 5.1	14.5 ± 5.5	15.8 ± 6.3	16.6 ± 6.3	***< 0.001****
Total Bodies	50.8 ± 11.6	49.2 ± 10.8	50.0 ± 11.2	52.0 ± 12.0	55.0 ± 12.8	***< 0.001****

groups: "Young" (18–29 years), "Adult" (29–42 years), "Middle-aged" (42–58 years) and "Older" (>58 years) [25, 26]. The segmental angles and relative contributions of discs and vertebral bodies to Upper, Middle, Lower, and total TK were compared between groups using ANOVAs for normally distributed variables or Kruskal-Wallis tests otherwise. Post-hoc analyses were performed using pairwise t-tests for normally distributed variables or Wilcoxon's tests otherwise, with Bonferroni correction.

The cohort was also stratified using Jenks method into four TK groups: "Low" (<41°), "Average-low" (41°−51°), "Average-high" (51°−63°), and "High" (>63°). The same analyses as for age groups were carried out according to TK groups.

Finally, a multivariate analysis including age and TK magnitude was conducted to determine the relative contribution of discs and vertebral bodies to TK. The statistical analysis was carried out using RStudio (Version 2023.09.1+494), with p-values lower than 0.05 considered significant.

Results

Cohort description (Tables 1 and 2; Figs. 1 and 2)

Out of the 879 subjects in the database, 645 were eligible and included in the current analysis, of whom 329 were females (51%), (Fig. 2).

Table 2 Median (IQR) contribution of discs and vertebral bodies to thoracic kyphosis for upper TK, middle TK, lower TK and total TK according to age. Significant p-values from ANOVA or Kruskal-Wallis analyses are denoted with an asterisk if<0.05

Age Groups	Cohort (n=645)	Young (n=291)	Adult >(n=139)	Middle-Aged (n=112)	Older (n=103)	p-values
Disc contribution to thoracic kyphosis (%)						
Upper TK (%)	**9.8** (−13.0–30.8)	**9.8** (−14.0–29.1)	**13.0** (−9.8–32.1)	**3.5** (−22.5–28.8)	**14.3** (−3.9–32.0)	*0.26*
Middle TK (%)	**20.3** (10.5–29.4)	**21.1** (11.7–28.9)	**17.7** (9.5–28.5)	**21.1** (9.9–29.2)	**20.6** (11.7–34.2)	*0.40*
Lower TK (%)	**−50.3** (−143.8– −3.3)	**−51.8** (−173.3– −3.8)	**−54.7** (−127.0– −10.9)	**−43.4** (−199.2–2.3)	**−40.6** (−102.9–7.7)	*0.49*
Total Disc TK (%)	**0.6** (−13.0–12.6)	**−0.8** (−13.6–13.2)	**2.7** (−10.7–12.3)	**0.2** (−14.5–11.7)	**2.5** (−11.6–11.6)	*0.74*
Vertebral body contribution to thoracic kyphosis (%)						
Upper TK (%)	**90.2** (69.2–113.5)	**90.2** (70.9–114.0)	**87.0** (67.9–109.8)	**96.5** (71.2–122.5)	**85.7** (68.0–103.9)	*0.26*
Middle TK (%)	**79.7** (70.6–89.5)	**79.0** (71.1–88.3)	**82.3** (71.5–90.5)	**78.9** (70.8–90.1)	**79.4** (65.8–88.3)	*0.40*
Lower TK (%)	**150.3** (103.3–243.8)	**151.8** (103.8–273.3)	**154.7** (110.9–227.0)	**143.4** (97.7–299.2)	**140.6** (92.3–202.9)	*0.49*
Total Body TK (%)	**99.4** (87.4–113.0)	**100.8** (86.8–113.6)	**97.3** (87.7–110.7)	**99.9** (88.3–114.5)	**97.5** (88.4–111.6)	*0.74*

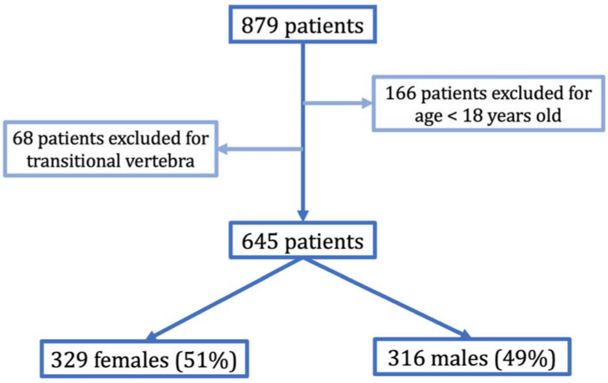

Fig. 2 Flow chart

In the entire cohort, the mean age was 37.6±16.3 years, and the mean BMI was 24.6±4.5 kg/m^2. The mean TK was 50.9±10.9°, the mean LL was −56.9±11.3°, and the mean PI was 49.2±9.5°. The mean Upper TK was 19.6±8.1°, the mean Middle TK was 23.4±7.1°, and the mean Lower TK was 7.9±7.7°. The most frequent thoracic apex locations were T6 and T7 in 34.7% and 33.2%, respectively. There was a significant correlation between TK and LL with a value of −0.31 ($p<0.001$). PI was not correlated with total TK ($p=0.41$), nor with any of the 3 TK regions. There was no significant association of PI with vertebral bodies or discs' contributions for the total TK ($p=0.27$ for both), nor in any of the TK regions (Upper, Middle and Lower). There was a weak but significant correlation between age and TK ($r=0.2$; $p<0.001$), Upper TK ($r=0.06$; $p=0.15$), Middle TK ($r=0.16$; $p<0.001$), Lower TK ($r=0.07$; $p=0.07$).

Discs kyphosis and discs contribution

On average, the sum of the discs in Upper and Middle TK was kyphotic with a mean value of 2.1±6.9° and 4.9±4.5° respectively whereas discs were lordotic in Lower TK with a mean value of −6.9±5.7° (Table 1). Disc contributions to Upper and Middle TK were 9.8% and 20.3% respectively (Table 2). Upper and Middle TK discs contributions to total TK were respectively 4.2% and 9.6%, representing a total of 13.8% of total kyphosis with a mean value of 7.0±8.5° (Tables 1 and 2). As Lower TK discs were lordotic, their participation in lower TK was −50.3% and −13.2% of total TK, leading to an overall disc contribution to TK of 0.6% (Table 2). Discs contribution was therefore maximal in Middle TK, where kyphosis was the greatest.

Vertebral bodies kyphosis and contribution

Conversely to the discs, vertebral bodies were all kyphotic. The sum of vertebral bodies was kyphotic with a mean value of 17.5±7.9° in Upper TK, 18.5±5.6° in Middle TK and 14.8±5.7° in Lower TK for a total of 50.8±11.6° in total kyphosis (Table 1). There was a major vertebral bodies contribution to TK in Upper and Middle TK with respective values of 90.2% and 79.7%. In the lower thoracic spine, since kyphotic vertebral bodies compensated for lordotic discs, vertebral bodies contribution to Lower TK was 150.3% (Table 2). The most important contribution to Total TK came therefore from vertebral bodies with a value of 99.4% in the cohort (Table 2). ***Appendix 1*** shows the segmental values for each vertebral body and disc, the regional

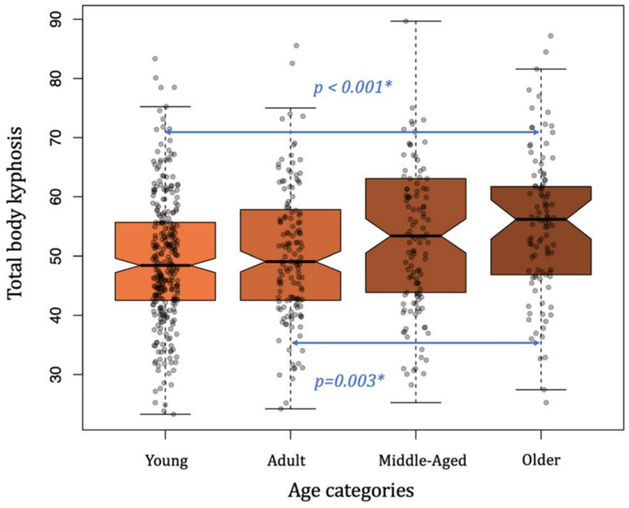

Fig. 3 Total body kyphosis by age categories. Blue double arrows represented the significant differences between age groups

Table 3 Median (IQR) contribution of discs and vertebral bodies to thoracic kyphosis for upper TK, middle TK, lower TK, and total TK according to sex. Significant p-values from ANOVA or Kruskal-Wallis analyses are written in bold and denoted with an asterisk if < 0.05

Sex Comparison	Female ($n=329$)	Male ($n=316$)	p-values
Disc contribution to thoracic kyphosis (%)			
Upper TK (%)	**3.2** (−22.6–22.8)	**17.5** (−3.1–37.6)	***<0.001****
Middle TK (%)	**18.8** (9.2–28.9)	**21.9** (13.8–31.0)	***0.02****
Lower TK (%)	**−42.6** (−126.5–2.9)	**−61.5** (−156.9– −8.2)	*0.08*
Total Disc TK (%)	**−1.8** (−14.4–11.1)	**2.6** (−10.4–13.5)	***0.01****
Vertebral body contribution to thoracic kyphosis (%)			
Upper TK (%)	**96.8** (77.2–122.6)	**82.5** (62.4–103.1)	***<0.001****
Middle TK (%)	**81.2** (71.1–90.8)	**78.1** (69.0–86.2)	***0.02****
Lower TK (%)	**142.6** (97.1–226.5)	**161.5** (108.2–256.9)	*0.08*
Total Body TK (%)	**101.8** (88.9–114.4)	**97.4** (86.5–110.4)	***0.01****

kyphosis values with their respective contributions, and the overall kyphosis value.

Age group analysis

There was no significant difference in disc kyphosis or in disc contribution with age ($p=0.72$ and $p=0.74$ respectively), (Tables 1 and 2). Vertebral bodies kyphosis increased across age groups for Middle TK ($p=0.004$), Lower TK ($p<0.001$), and Total TK ($p<0.001$), but not for Upper TK (Table 1 ***and*** Fig. 3). The post-hoc analysis revealed that vertebral bodies were more kyphotic for the Total TK in the older group compared to young ($p<0.001$) and adult subjects ($p=0.003$), (Fig. 3).

Sex comparison (Table 3)

Discs contribution to total TK was significantly higher in males than females, with respective values of 2.6% and − 1.8% ($p=0.01$), (Table 3). Differences were more pronounced in the most kyphotic regions, with respective values of 17.5% versus 3.2% in Upper TK ($p<0.001$) and 21.9% versus 18.8% in Middle TK ($p=0.02$), (Table 3). Vertebral bodies contribution was higher in females than males with respective values of 101.8% and 97.4% ($p=0.01$), (Table 3).

TK groups analysis (Tables 4 and 5)

The four TK groups were: "Low" (<41°), "Average-low" (41°–51°), "Average-high" (51°–63°), "High" (>63°). Discs kyphosis and vertebral bodies kyphosis both increased significantly with increasing TK ($p<0.001$), (Table 4). Discs contributions to total TK increased significantly with increasing TK ($p<0.001$) with respective values across TK groups of −13.8% for Low TK, −1.5% for Average-Low TK, 5.7% for Average-High TK and 9.1% for High TK, (Table 5 ***and*** Fig. 4). Moreover, vertebral bodies contribution decreased with increasing TK ($p<0.001$), with respective values across TK groups of 113.8% for Low TK, 101.5% for Average-Low TK, 94.3% for Average-High TK and 90.9% for High TK, (Table 5 ***and*** Fig. 4). These differences were more important in Upper TK with values ranging from − 1.7% to 15% ($p=0.002$), and Middle TK with values ranging from 15.5% to 23.5% ($p<0.001$), where kyphosis was the highest (Table 5).

Age significantly increased with TK groups ($p=0.001$), (Table 4). Multivariate analysis demonstrated that discs contribution increased with increasing TK, while controlling for age ($p<0.001$).

Discussion

Our results address the gap in the literature concerning TK by providing the first detailed description of discs and vertebral bodies contributions to TK and their variation according to age, sex and thoracic kyphosis magnitude, in a large cohort of asymptomatic adults. Among these 645 subjects, intervertebral discs were found to be kyphotic in Upper and Middle TK with respective discs contribution to total TK of 4.2% and 9.6%, for a total of 13.8% of total kyphosis. However, Lower TK discs were lordotic, with a participation of

Table 4 Mean ± SD segmental Cobb angles (expressed in degree) for upper TK, middle TK, lower TK and total TK according to TK groups. Significant p-values, issues from ANOVA or Kruskal-Wallis analyses are written in bold and denoted with an asterisk if < 0.05

TK groups	Low (n = 110)	Average-Low (n = 227)	Average-High (n = 227)	High (n = 81)	p-values
Segmental disc angle in thoracic kyphosis (°)					
Upper TK	0.1 ± 7.5	1.4 ± 6.5	3.3 ± 6.7	3.1 ± 6.7	**< 0.001***
Middle TK	2.6 ± 4.7	4.4 ± 4.0	5.7 ± 4.2	7.3 ± 4.3	**< 0.001***
Lower TK	−9.2 ± 5.5	−7.4 ± 5.8	−6.1 ± 5.5	−5.1 ± 5.6	**< 0.001***
Total Discs	−6.5 ± 10.3	−1.6 ± 8.9	2.9 ± 9.6	5.3 ± 9.9	**< 0.001***
Segmental vertebral body angle in thoracic kyphosis (°)					
Upper TK	14.4 ± 7.3	16.2 ± 7.2	18.6 ± 7.9	22.1 ± 7.5	**< 0.001***
Middle TK	15.2 ± 4.8	17.7 ± 4.9	19.1 ± 4.9	23.9 ± 6.0	**< 0.001***
Lower TK	12.2 ± 4.8	13.9 ± 5.1	15.7 ± 5.7	18.0 ± 6.3	**< 0.001***
Total Bodies	41.8 ± 9.9	47.7 ± 8.9	53.4 ± 9.8	64.1 ± 10.1	**< 0.001***
Age (years)					
Age	32.9 ± 13.2	36.9 ± 15.9	38.2 ± 15.9	44.1 ± 19.9	**0.001***

Table 5 Median (IQR) contribution to thoracic kyphosis for upper TK, middle TK and lower TK according to TK groups. Significant p-values, issues from ANOVA or Kruskal-Wallis analyses are denoted with an asterisk if < 0.05

TK groups	Low (n = 110)	Average-Low (n = 227)	Average-High (n = 227)	High (n = 81)	p-values
Disc contribution to thoracic kyphosis (%)					
Upper TK (%)	**−1.7** (−33.9–28.3)	**10.5** (−20.6–29.7)	**15.0** (−3.3–32.6)	**11.0** (−4.1–28.1)	**0.002***
Middle TK (%)	**15.5** (−3.8–27.7)	**18.1** (10.5–27.8)	**22.0** (13.8–32.0)	**23.5** (16.3–30.7)	**< 0.001***
Lower TK (%)	**−66.6** (−223.4–148.0)	**−53.9** (−182.5– −3.6)	**−50.3** (−134.9– −11.8)	**−35.1** (−81.1– −3.3)	0.11
Total Disc TK (%)	**−13.8** (−36.5–1.0)	**−1.5** (−16.3–9.9)	**5.7** (−8.4–16.1)	**9.1** (−5.1–18.1)	**< 0.001***
Vertebral body contribution to thoracic kyphosis (%)					
Upper TK (%)	**101.8** (71.7–133.9)	**89.5** (70.3–120.6)	**85.0** (67.4–103.4)	**89.0** (71.9–104.1)	**0.002***
Middle TK (%)	**84.5** (72.3–103.8)	**81.9** (72.1–89.5)	**78.0** (68.0–86.2)	**76.5** (69.3–83.7)	**< 0.001***
Lower TK (%)	**166.6** (−48.0–323.4)	**153.9** (103.6–282.5)	**150.3** (111.8–234.9)	**135.1** (103.3–180.1)	0.11
Total Body TK (%)	**113.8** (99.0–136.5)	**101.5** (90.2–116.3)	**94.3** (83.9–108.4)	**90.9** (81.9–105.1)	**< 0.001***

−13.2% of total TK, leading to an overall discs contribution to TK of 0.6%. Vertebral bodies were all kyphotic with a contribution of 99.4% of total kyphosis. This study also showed that age association with thoracic kyphosis was greater for vertebral bodies than discs. This study is the first to our knowledge to show that disc contribution to thoracic kyphosis increases significantly with increasing thoracic kyphosis magnitude. Finally, discs contribution was significantly greater in males than in females.

This study found that the vertebral bodies contributed up to 99.4% of the total thoracic kyphosis (TK), while the discs contribution was negligeable (0.6%). However, one characteristic of the discs revealed in this study is their varying angulation: kyphotic in the Upper and Middle TK, and lordotic in the Lower TK. These findings align with those from Goh et al. who, in a review of 93 lateral radiographs, reported that vertebral morphology was highly predictive of thoracic curvature, while disc morphology had a weaker association, and that these differences were larger in mid-thoracic region [27]. Similarly, in a recent study on 32 patients with degenerative thoraco-lumbar deformity, He et al. reported a total vertebral bodies contribution of 94.23%, for a disc contribution of only 5.77% [18]. Other studies have confirmed the kyphotic nature of thoracic vertebrae in different populations [28, 29].

It is well known that thoracic kyphosis tends to increase with physiological aging [30–33]. In this study, significant association between age and thoracic kyphosis was observed, with a greater contribution of vertebral bodies than discs, particularly in the Middle, Lower and Total TK. This accentuation of kyphosis seems more linked to bony component than disc. Regarding the bony component, some

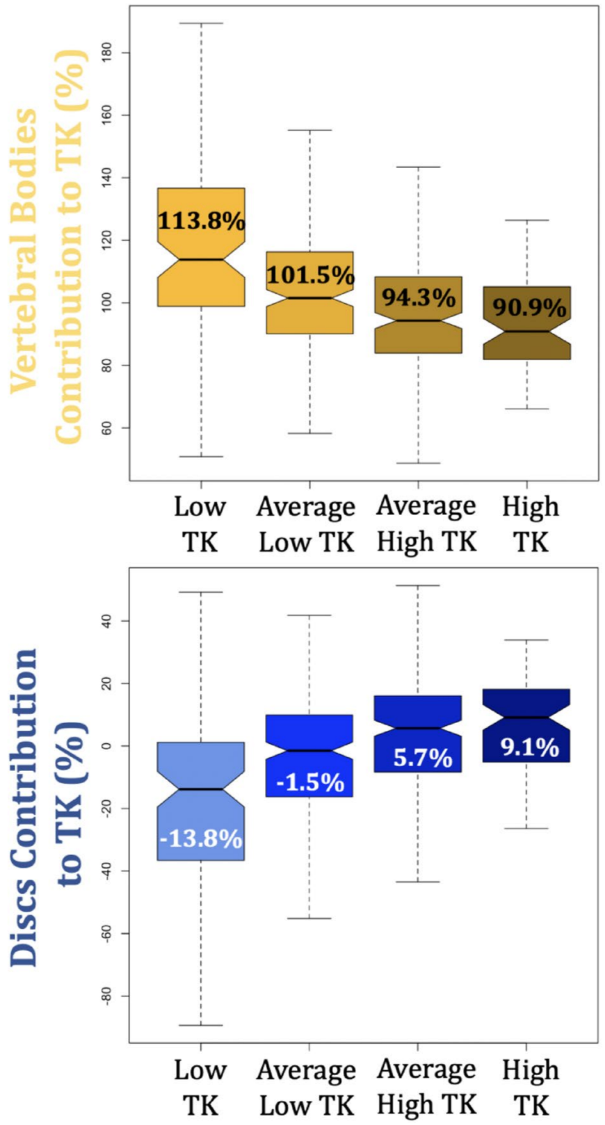

Fig. 4 Discs and Vertebral bodies contributions to Thoracic Kyphosis according to TK groups (Low, Average-Low, Average-High and High). Decrease in discs contribution and increase in vertebral bodies contribution are associated with an increase in TK

authors attribute this increase to osteoporosis, especially vertebral fractures, which are more common in the middle and lower thoracic region [34, 35]. In addition, the asymptomatic nature of many osteoporotic fractures, as confirmed by several studies, explain the increase in thoracic kyphosis with age in our healthy volunteer population [36]. Furthermore, increased stresses on the anterior aspect of the vertebral body could increase bone remodeling in cases of low bone density [37]. Additionally, other studies have suggested that increased kyphosis may be related to decreased muscle integrity in elderly population, contributing to poor posture, which in turn can lead to increased compressive load on thoracic and thoraco-lumbar spine over time [33, 38–40].

This study also showed that the contribution of discs was greater in males than in females. Schmorl and Junghan, in their book, explained that age-related kyphosis was associated with loss of disc height in males without osteoporosis [41]. This assertion has been confirmed by several authors, who found a higher rate of disc degeneration in males, as well as a greater rate of thoracic disc herniation [42–45]. In a recent study of 2016, Strömqvist et al., found out of 15,631 patients operated for disc herniation a male rate of 56% [46]. Manns et al. highlighted that disc degeneration is a physiological and often asymptomatic process beginning at first with concentric tears in the anterior parts of the discs and resulting in anterior disc bulging that then progresses to fibrosis [17]. Goh et al. showed that these anomalies occurred mostly in mid and lower thoracic kyphosis [42]. Other authors confirmed the greater contribution of bony kyphosis in females, attributing this to asymptomatic osteoporotic fractures, related to hormonal factors such as the decrease in estrogen, which leads to a reduction in bone density [17, 34, 35]. Stone et al. found that bone mineral density was an independent risk factor for increased thoracic kyphosis leading to discussions about preventive osteoporosis treatments [47]. However, in that same recent study, the authors suggested a probable genetic component, which may not be corrected with treatment, corroborating Manns et al.'s results [17, 47]. In these osteoporotic patients scheduled for ASD surgery, hormone therapy is therefore indicated as a preventive measure to limit the hyperkyphosis associated with these processes.

This study also showed that larger kyphosis was associated to a greater discs contribution to TK. To our knowledge, this finding has not been previously reported in literature. Liu et al. reported in a population of ankylosing spondylitis patients that vertebral bodies contribution was greater when the overall kyphosis was greater than 70°; however, this was a very specific pathological population [48]. While the current study was conducted in a cohort of asymptomatic subjects, it would be interesting to observe how the discs and vertebral bodies contribution changes with progression of sagittal malalignment and activation of thoracic compensation mechanisms. These questions represent an important area of future investigation and could help to understand junctional complications, given the burden of proximal junctional kyphosis (PJK) in adult deformity surgery. Despite recent efforts to understand its pathogenesis, risk factors, prevention, and treatment, PJK remains a frequent complication, occurring in 23% to 41% of patients undergoing surgery for spinal deformity [49]. Increased thoracic kyphosis has been identified as an important predictor of PJK [50] but this may be an oversimplification of a complex morphological issue. Increasing TK results in higher discs contribution, allowing greater micro-mobility within the construct and at its proximal end, which could potentially explain this risk factor.

Limitations

This study has several limitations. First its cross-sectional nature does not permit to investigate the effects of aging on thoracic kyphosis. In addition, this study did not use MRI, CT scans which could have provided a more accurate assessment of disc and vertebral degeneration. In this study, the volunteers were only healthy volunteers who did not complain of any spinal pain and who had no history of trauma or vertebral fracture. However, undetected vertebral compression fracture can contribute to a TK increase and it is difficult to separate them from vertebral degeneration. No assessment of bone mineral density was carried out, which would have allowed to correlate the results with possible osteopenia or osteoporosis. However, biplanar radiography allowed to evaluate the spine in standing position.

Conclusion

This study highlights the predominant role of vertebral bodies contribution to thoracic kyphosis, 99.4% on average. The contribution of disc to thoracic kyphosis (values ranging from −13.8% to 9.1%) increases significantly with increasing thoracic kyphosis magnitude. The association of age with thoracic kyphosis was greater for vertebral bodies than discs, particularly in Middle and Lower TK. Finally, discs contribution was greater in males than in females, which may be attributed to a higher rate of disc degeneration in males and the presence of asymptomatic osteoporotic fractures in females. These findings provide a foundation for improving treatments of degenerative thoracic kyphosis and pathological hyper kyphosis. The data from this study may help reduce the risk of PJK by evaluating in further studies the deviation from normal discs and vertebral bodies contribution in patients with deformity and PJK.

Appendix

See Table 6.

Table 6 Segmental (vertebral body and disc), regional and global sagittal alignments of asymptomatic volunteers. Percentages of the different regional TKs were expressed versus T1-L1. Kyphotic angles were reported with positive values and lordotic angle with negative values

Segmental (°)		Regional (°)		Global (°)
T1 body	6.5 ± 3.8	**Upper TK (T1-T5)**	19.6 ± 8.1 (38.9 ± 14.9% of Global TK)	**T1-L1 TK** 50.9 ± 10.9
T1-T2 disc	−1.7 ± 3.4			
T2 body	3.9 ± 3.1			
T2-T3 disc	0.6 ± 3.0			
T3 body	3.2 ± 2.8			
T3-T4 disc	1.4 ± 2.3			
T4 body	4.3 ± 2.2			
T4-T5 disc	1.5 ± 2.5			
T5 body	4.5 ± 2.6	**Middle TK (T5-T9)**	23.4 ± 7.1 (46.8 ± 12.1% of Global TK)	
T5-T6 disc	1.9 ± 1.9			
T6 body	4.6 ± 2.2			
T6-T7 disc	1.4 ± 1.8			
T7 body	5.0 ± 2.1			
T7-T8 disc	1.5 ± 1.6			
T8 body	4.7 ± 2.0			
T8-T9 disc	0.1 ± 1.7			
T9 body	3.2 ± 2.1	**Lower TK (T9-L1)**	7.9 ± 7.7 (14.3 ± 14.4% of Global TK)	
T9-T10 disc	−0.6 ± 1.8			
T10 body	3.3 ± 2.4			
T10-T11 disc	−1.1 ± 2.1			
T11 body	4.2 ± 2.3			
T11-T12 disc	−1.8 ± 2.4			
T12 body	4.1 ± 2.3			
T12-L1 disc	−3.7 ± 2.5			

Author contributions A wrote the main manuscript text and prepared figures and tables.B to J help to collected the data, prepared figures and tables and reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Competing interests The authors declare no competing interests.

References

1. Abelin-Genevois K (2021) Sagittal balance of the spine. Orthop Traumatol Surg Res. https://doi.org/10.1016/J.OTSR.2020.102769
2. Schwab JH (2017) Global sagittal alignment. Skeletal Radiol 46:1613–1614. https://doi.org/10.1007/S00256-017-2752-0
3. Lee CH, Chung CK, Jang JS, Kim SM, Chin DK, Lee JK (2017) Lumbar degenerative kyphosis is not byword for degenerative sagittal imbalance: time to replace a misconception. J Korean Neurosurg Soc 60:125–129. https://doi.org/10.3340/JKNS.2016.0607.001
4. Sebaaly A, Grobost P, Mallam L, Roussouly P (2018) Description of the sagittal alignment of the degenerative human spine. Eur Spine J 27:489–496. https://doi.org/10.1007/S00586-017-5404-0
5. Le Huec JC, Thompson W, Mohsinaly Y, Barrey C, Faundez A (2019) Sagittal balance of the spine. Eur Spine J 28:1889–1905. https://doi.org/10.1007/S00586-019-06083-1
6. Barrey C, Roussouly P, Perrin G, Le Huec JC (2011) Sagittal balance disorders in severe degenerative spine. Can we identify the

compensatory mechanisms? Eur Spine J 20(S5):626–633. https://doi.org/10.1007/S00586-011-1930-3
7. Beyer G, Khalifé M, Lafage R, Yang J, Elysee J, Frangella N et al (2020) Pelvic compensation in sagittal malalignment: how much retroversion can the pelvis accommodate? Spine (Phila Pa 1976) 45:E203–E209. https://doi.org/10.1097/BRS.0000000000003228
8. Faundez A (2011) Analyse de l'équilibre sagittal du rachis. Orthopédie 322:2470–2474
9. Iyer S, Lenke LG, Nemani VM, Albert TJ, Sides BA, Metz LN et al (2016) Variations in sagittal alignment parameters based on age: a prospective study of asymptomatic volunteers using full-body radiographs. Spine (Phila Pa 1976) 41:1826–1836. https://doi.org/10.1097/BRS.0000000000001642
10. Vialle R, Levassor N, Rillardon L, Templier A, Skalli W, Guigui P (2005) Radiographic analysis of the sagittal alignment and balance of the spine in asymptomatic subjects. J Bone Joint Surg Am 87:260–267. https://doi.org/10.2106/JBJS.D.02043
11. Boulay C, Tardieu C, Hecquet J, Benaim C, Mouilleseaux B, Marty C et al (2006) Sagittal alignment of spine and pelvis regulated by pelvic incidence: standard values and prediction of lordosis. Eur Spine J 15:415–422. https://doi.org/10.1007/S00586-005-0984-5
12. Lafage R, Schwab F, Challier V, Henry JK, Gum J, Smith J et al (2016) Defining spino-Pelvic alignment thresholds: should operative goals in adult spinal deformity surgery account for age? Spine (Phila Pa 1976) 41:62–68. https://doi.org/10.1097/BRS.0000000000001171
13. Lafage R, Schwab F, Glassman S, Bess S, Harris B, Sheer J et al (2017) Age-adjusted alignment goals have the potential to reduce PJK. Spine (Phila Pa 1976) 42:1275–1282. https://doi.org/10.1097/BRS.0000000000002146
14. Faundez A, Roussouly P, Le Huec JC (2011) Sagittal balance of the spine: a therapeutic revolution. Rev Med Suisse 7:2470–2474
15. Sebaaly A, Silvestre C, Rizkallah M, Grobost P, Chevillotte T, Kharrat K et al (2021) Revisiting thoracic kyphosis: a normative description of the thoracic sagittal curve in an asymptomatic population. Eur Spine J 30:1184–1189. https://doi.org/10.1007/S00586-020-06670-7
16. Lafage R, Steinberger J, Pesenti S, Assi A, Elysee JC, Iyer S et al (2020) Understanding thoracic spine morphology, shape, and proportionality. Spine (Phila Pa 1976) 45:149–157. https://doi.org/10.1097/BRS.0000000000003227
17. Manns RA, Haddaway MJ, McCall IW, Pullicino VC, Davie MWJ (1996) The relative contribution of disc and vertebral morphometry to the angle of kyphosis in asymptomatic subjects. Clin Radiol 51:258–262. https://doi.org/10.1016/S0009-9260(96)80342-4
18. He S-Y, Li H-D, Min J-K, Luo S-C, Dai J-L (2023) [Effect of morphological changes in the sagittal plane of vertebrae and discs on degenerative kyphodeformity]. Zhongguo Gu Shang 36:653–657. https://doi.org/10.12200/J.ISSN.1003-0034.2023.07.011
19. Chaibi Y, Cresson T, Aubert B, Hausselle J, Neyret P, Hauger O et al (2012) Fast 3D reconstruction of the lower limb using a parametric model and statistical inferences and clinical measurements calculation from biplanar X-rays. Comput Methods Biomech Biomed Engin 15:457–466. https://doi.org/10.1080/10255842.2010.540758
20. Humbert L, De Guise JA, Aubert B, Godbout B, Skalli W (2009) 3D reconstruction of the spine from biplanar x-rays using parametric models based on transversal and longitudinal inferences. Med Eng Phys 31:681–687. https://doi.org/10.1016/J.MEDENGPHY.2009.01.003
21. Ferrero E, Lafage R, Vira S, Rohan PY, Oren J, Delsole E et al (2017) Three-dimensional reconstruction using stereoradiography for evaluating adult spinal deformity: a reproducibility study. Eur Spine J 26:2112–2120. https://doi.org/10.1007/S00586-016-4833-5
22. Quijano S, Serrurier A, Aubert B, Laporte S, Thoreux P, Skalli W (2013) Three-dimensional reconstruction of the lower limb from biplanar calibrated radiographs. Med Eng Phys 35:1703–1712. https://doi.org/10.1016/J.MEDENGPHY.2013.07.002
23. Pesenti S, Charles YP, Prost S, Solla F, Blondel B, Ilharreborde B (2023) Spinal sagittal alignment changes during childhood: results of a national cohort analysis of 1,059 healthy children. J Bone Joint Surg Am 105:676–686. https://doi.org/10.2106/JBJS.22.00977
24. Khalifé M, Skalli W, Assi A, Guigui P, Attali V, Valentin R et al (2024) Sex-dependent evolution of whole-body postural alignment with age. Eur Spine J. https://doi.org/10.1007/s00586-024-08323-5
25. Krzywinski M, Altman N (2014) Visualizing samples with box plots. Nat Methods 11:119–120. https://doi.org/10.1038/nmeth.2813
26. McCrum ML, Wan N, Han J, Lizotte SL, Horns JJ (2022) Disparities in spatial access to emergency surgical services in the US. JAMA Health Forum 3:e223633. https://doi.org/10.1001/jamahealthforum.2022.3633
27. Goh S, Price RI, Leedman PJ, Singer KP (1999) The relative influence of vertebral body and intervertebral disc shape on thoracic kyphosis. Clin Biomech (Bristol Avon) 14:439–448. https://doi.org/10.1016/S0268-0033(98)00105-3
28. Panjabi MM, Takata K, Goel V, Federico D, Oxland T, Duranceau J et al (1991) Thoracic human vertebrae. Quantitative three-dimensional anatomy. Spine (Phila Pa 1976) 16:888–901. https://doi.org/10.1097/00007632-199108000-00006
29. Tan SH, Teo EC, Chua HC (2004) Quantitative three-dimensional anatomy of cervical, thoracic and lumbar vertebrae of Chinese Singaporeans. Eur Spine J 13:137–146. https://doi.org/10.1007/S00586-003-0586-Z
30. Khalifé M, Skalli W, Assi A, Guigui P, Attali V, Valentin R et al Sex-dependent evolution of whole-body postural alignment with age. Eur Spine J 2024. https://doi.org/10.1007/S00586-024-08323-5
31. Milne JS, Lauder IJ (1974) Age effects in kyphosis and lordosis in adults. Ann Hum Biol 1:327–337. https://doi.org/10.1080/03014467400000351
32. Bassani T, Galbusera F, Luca A, Lovi A, Gallazzi E, Brayda-Bruno M (2019) Physiological variations in the sagittal spine alignment in an asymptomatic elderly population. Spine J 19:1840–1849. https://doi.org/10.1016/j.spinee.2019.07.016
33. Roghani T, Zavieh MK, Manshadi FD, King N, Katzman W (2017) Age-related hyperkyphosis: update of its potential causes and clinical impacts-narrative review. Aging Clin Exp Res 29:567–577. https://doi.org/10.1007/s40520-016-0617-3
34. De Smet AA, Robinson RG, Johnson BE, Lukert BP (1988) Spinal compression fractures in osteoporotic women: patterns and relationship to hyperkyphosis. Radiology 166:497–500. https://doi.org/10.1148/RADIOLOGY.166.2.3336728
35. Hedlund LR, Gallagher JC, Meeger C, Stoner S (1989) Change in vertebral shape in spinal osteoporosis. Calcif Tissue Int 44:168–172. https://doi.org/10.1007/BF02556559
36. Gershon Cohen J, Rechtman AM, Schraer H, Blumberg N (1953) Asymptomatic fractures in osteoporotic spines of the aged. J Am Med Assoc 153:625–627. https://doi.org/10.1001/JAMA.1953.02940240017005
37. Kolta S, Kerkeni S, Travert C, Skalli W, Eastell R, Glüer CC et al (2012) Variations in vertebral body dimensions in women measured by 3D-XA: a longitudinal in vivo study. Bone 50:777–783. https://doi.org/10.1016/j.bone.2011.12.005
38. Miyagi M, Inoue G, Hori Y, Inage K, Murata K, Kawakubo A et al (2022) Decreased muscle mass and strength affected spinal

sagittal malalignment. Eur Spine J 31:1431–1437. https://doi.org/10.1007/S00586-022-07151-9
39. Lam JC, Mukhdomi T, Kyphosis (2024)
40. Milne JS, Lauder IJ (1976) The relationship of kyphosis to the shape of vertebral bodies. Ann Hum Biol 3:173–179. https://doi.org/10.1080/03014467600001281
41. Schmorl G, Junghanns H (1971) The human spine in health and disease, 2nd edn. Grune & Stratton, New York
42. Goh S, Tan C, Price RI, Edmondston SJ, Song S, Davis S et al (2000) Influence of age and gender on thoracic vertebral body shape and disc degeneration: an MR investigation of 169 cases. J Anat 197:647–657. https://doi.org/10.1046/J.1469-7580.2000.19740647.X
43. Wood KB, Garvey TA, Gundry C, Heithoff KB (1995) Magnetic resonance imaging of the thoracic spine. Evaluation of asymptomatic individuals. J Bone Joint Surg Am 77:1631–1638. https://doi.org/10.2106/00004623-199511000-00001
44. Brown CW, Deffer PA, Akmakjian J, Donaldson DH, Brugman JL (1992) The natural history of thoracic disc herniation. Spine (Phila Pa 1976) 17:97–102. https://doi.org/10.1097/00007632-199206001-00006
45. Martucci E, Mele C, Martella P (1960) Thoracic intervertebral disc protrusion: a clinical study. J Neurosurg 17:333–339. https://doi.org/10.3171/JNS.1960.17.3.0418
46. Strömqvist F, Strömqvist B, Jönsson B, Karlsson MK (2016) Gender differences in patients scheduled for lumbar disc herniation surgery: a national register study including 15,631 operations. Eur Spine J 25:162–167. https://doi.org/10.1007/S00586-015-4052-5
47. Stone MA, Osei-Bordom DC, Inman RD, Sammon C, Wolber LE, Williams FMK (2015) Heritability of spinal curvature and its relationship to disc degeneration and bone mineral density in female adult twins. Eur Spine J 24:2387–2394. https://doi.org/10.1007/S00586-014-3477-6
48. Liu H, Qian BP, Qiu Y, Wang Y, Wang B, Yu Y et al (2016) Vertebral body or intervertebral disc wedging: which contributes more to thoracolumbar kyphosis in ankylosing spondylitis patients? A retrospective study. Medicine. https://doi.org/10.1097/MD.0000000000004855
49. Liu FY, Wang T, Yang SD, Wang H, Yang DL, Ding WY (2016) Incidence and risk factors for proximal junctional kyphosis: a meta-analysis. Eur Spine J 25:2376–2383. https://doi.org/10.1007/S00586-016-4534-0
50. Mendoza-Lattes S, Ries Z, Gao Y, Weinstein SL (2011) Proximal junctional kyphosis, in adult reconstructive spine surgery results from incomplete restoration of the lumbar lordosis relative to the magnitude of the thoracic kyphosis. Iowa Orthop J 31:199

Authors and Affiliations

Mikael Finoco[1,2] · Renaud Lafage[2] · Claudio Vergari[3] · Wafa Skalli[3] · Jonathan Elysée[2] · Ayman Assi[4] · Pierre Guigui[1] · Emmanuelle Ferrero[1] · Virginie Lafage[2] · Marc Khalife[1,2]

✉ Mikael Finoco
mikael.finoco@gmail.com

Renaud Lafage
renaud.lafage@gmail.com

Claudio Vergari
claudio.vergari@ensam.eu

Wafa Skalli
wafa.skalli@gmail.com

Jonathan Elysée
elysee.jonathan@gmail.com

Ayman Assi
ayman.assi@gmail.com

Pierre Guigui
pierre.guigui@aphp.fr

Emmanuelle Ferrero
emmanuelle.ferrero@gmail.com

Virginie Lafage
virginie.lafage@gmail.com

Marc Khalife
marc.khalife@aphp.fr

1 Hôpital Européen Georges-Pompidou, Paris, France

2 Lenox Hill Hospital, New York, USA

3 Arts et Metiers Institute of Technology, Paris, France

4 Saint Joseph University, Beirut, Lebanon