Eur Spine J (2018) 27:448–457
https://doi.org/10.1007/s00586-017-5156-x

ORIGINAL ARTICLE

Coronal plane trunk asymmetry is associated with whole-body sagittal alignment in healthy young adolescents before pubertal peak growth

Mieke Dolphens[1] · Andry Vleeming[1,2] · René Castelein[3] · Guy Vanderstraeten[1,4] · Tom Schlösser[3] · Frank Plasschaert[5] · Lieven Danneels[1]

Received: 16 August 2016 / Revised: 3 April 2017 / Accepted: 25 May 2017 / Published online: 3 June 2017

Abstract
Purpose To investigate coronal plane trunk asymmetry (TA) and its association with sagittal postural alignment in healthy subjects before pubertal peak growth.
Methods In this cross-sectional baseline study, 1190 healthy pre-peak growth velocity subjects were included. Coronal plane TA was evaluated using back surface topography. Whole-body sagittal alignment (previously validated and objectively classified as neutral, sway-back or leaning-forward) and sagittal spinopelvic profile (trunk lean, lumbar lordosis, thoracic kyphosis, sacral inclination and length of the posteriorly inclined thoracolumbar segment) were determined, as were height, proportion of trunk to body length, body mass index, generalized joint laxity, and handedness.
Results Logistic regression analysis yielded overall sagittal posture class to be independently associated with coronal plane TA: having a leaning-forward posture associated with a nearly three times higher odds of coronal TA ($p < 0.001$) compared to neutrals. A sway-back was 2.2 times more likely to show TA ($p = 0.016$) than a neutral, yet only in boys. Significant associations with coronal TA were also found for trunk lean, thoracic kyphosis and body mass index. These correlations, however, were gender and posture class specific. The spinal region where asymmetry is seen, varies according to the whole-body sagittal alignment type: primary thoracic curves were the most frequent in leaning-forwards, whereas primary curves in the lumbar or declive thoracolumbar segment were the most common in sway-backs.
Conclusions In immature spines without known scoliosis, coronal plane TA is associated with whole-body sagittal alignment. It is more often seen in non-neutral than neutral sagittal posture types. Whether adolescent idiopathic scoliosis is related with postural characteristics before pubertal growth peak, should be addressed in future prospective studies.

Keywords Posture · Postural balance · Spinal curvatures · Scoliosis · Growth and development

Electronic supplementary material The online version of this article (doi:10.1007/s00586-017-5156-x) contains supplementary material, which is available to authorized users.

✉ Mieke Dolphens
Mieke.Dolphens@UGent.be

1 Department of Rehabilitation Sciences and Physiotherapy, Faculty of Medicine and Health Sciences, Ghent University, Campus Heymans (UZ, 3B3), De Pintelaan 185, 9000 Ghent, Belgium

2 Department of Anatomy, Medical Faculty, Center of Excellence in Neuroscience, University of New England, Biddeford, ME, USA

3 Department of Orthopaedic Surgery, University Medical Center Utrecht, Utrecht, The Netherlands

4 Department of Physical and Rehabilitation Medicine, Faculty of Medicine and Health Sciences, Ghent University, Ghent, Belgium

5 Department of Orthopedics and Traumatology, Ghent University Hospital, Ghent, Belgium

Introduction

Adolescent idiopathic scoliosis (AIS) is a structural, three-dimensional curvature of the spine that manifests in otherwise healthy children at or around puberty [1]. Physiological trunk asymmetry (TA) and AIS form a continuum of TA with thresholds needed to prescribe abnormality. The Scoliosis Research Society defines AIS as a lateral curvature of more than 10° as measured by the Cobb technique on a standing anterior-posterior radiograph of the spine [1, 2]. AIS affects 1–3% of the at-risk population (children aged 10–16 years) [1, 3]. While most curves need no intervention, almost 10% of subjects with AIS do require treatment [1, 3]. A major concern in the management of AIS is to identify those (initially small) curves that will progress into significant deformity and require treatment. To meet that need, prospective research among healthy subjects is warranted, with baseline measurements before pubertal peak growth and before AIS diagnosis. Unfortunately, little of such research has yet been performed [4, 5].

Obviously, the etio-pathogenesis of AIS remains unknown due to its multifactorial complexity. It is, however, well appreciated that the sagittal spino-pelvic alignment may play an important role in spinal biomechanics, rotational stability of the growing spine and the development and progression of AIS [6–9]. Two spinal-pelvic features have typically been incriminated as contributors to rotational instability and the initiation of scoliosis: posterior inclination of the spine including the impact of posteriorly directed shear loads [8, 10] and (the mechanical load on) thoracic hypokyphosis [6]. The complexities of these relationships, however, are not fully understood. Shortcomings of earlier studies include (1) failure to directly relate coronal to sagittal plane posture in healthy subjects at crucial phases of growth since a slight pre-existent vertebral rotation or mild TA exists in the normal, non-scoliotic spine [11, 12]; (2) failure to consider the spinal-pelvic complex in the context of the whole body, and thus relative to gravity; and (3) studying patients with already established scoliosis or mixed coronal curve patterns compared to non-scoliotic controls. Therefore, the present study investigates coronal plane TA and its association with whole-body sagittal alignment in healthy boys and girls before pubertal peak growth. Since posture features at young age—most likely together with other factors or mechanisms—may be a precursor of AIS in some individuals [4], the present study might illuminate key issues for researchers and clinicians to consider in (progressive) TA and/or AIS.

Materials and methods

Study design and study population

We performed a cross-sectional observational study from September 2008 to February 2009 in Flanders, Belgium. Sixty-four schools were selected to represent educational networks and levels within Flemish mainstream education. Evaluation was accomplished at schools and local guidance centers. Ethical approval for the study was obtained from the ethics committee of the Ghent University Hospital.

The dataset includes data from 1196 healthy subjects (639 boys, aged 12.6 ± 0.5 years and 557 girls, aged 10.6 ± 0.5 years) and comprises a wide array of physical, sociodemographic, lifestyle, psychosocial and medical variables, including (psycho)somatic (pain) complaints [13, 14]. To investigate a homogenous male and female population in terms of growth phase, subjects were recruited according to a maturational benchmark [i.e., (predicted) age at PHV] [15]. Therefore, boys in year 1 of secondary education whereas girls in year 5 of primary education were eligible to participate. To restrict to healthy young adolescents, subjects were excluded from the study if they had neurological conditions, rheumatic disorders, metabolic or endocrine diseases, major congenital anomalies, skeletal disorders, connective tissue disorders, previous spinal fracture or previous spinal surgery. Children with apparent severe spinal asymmetry and known—radiographically confirmed—scoliosis, were excluded too. Written informed consent for participation in this research study was obtained from each subject and their parents or guardians before testing.

Measurements

Coronal plane TA was evaluated using back surface topography. Previous studies evaluating the validity and reliability of techniques based on surface topography demonstrated good accuracy compared with radiographs and a high reliability in healthy volunteers and AIS patients [16–18]. In the present study, TA was recorded in a standing position by evaluating the (deviation of the) palpated spinous process line with respect to central sacral vertical line on standardized dorsal 2-dimensional photographic images as shown in Fig. 1. Before photography, the spinous processes of C7–L5 were marked on the skin with a pen and reflective markers were placed on bony landmarks. Palpation and marker placement was done by a single trained health care professional with experience in palpation [13, 19]. All images were assessed by a single trained researcher (qualified as manual therapist and physical therapist specialized in orthopedic rehabilitation) who was blinded to the other study results when coronal plane posture was analyzed. When a visually observed TA was present, both the area and convexity of the asymmetry were documented. Similar to the classification of AIS on radiographs, truncal and spinal asymmetry types were defined as (1) primary thoracic curves, (2) primary (thoraco)lumbar curves, and (3) double [thoracic and (thoraco)lumbar] curves. Figure 1 displays a typical member from each type.

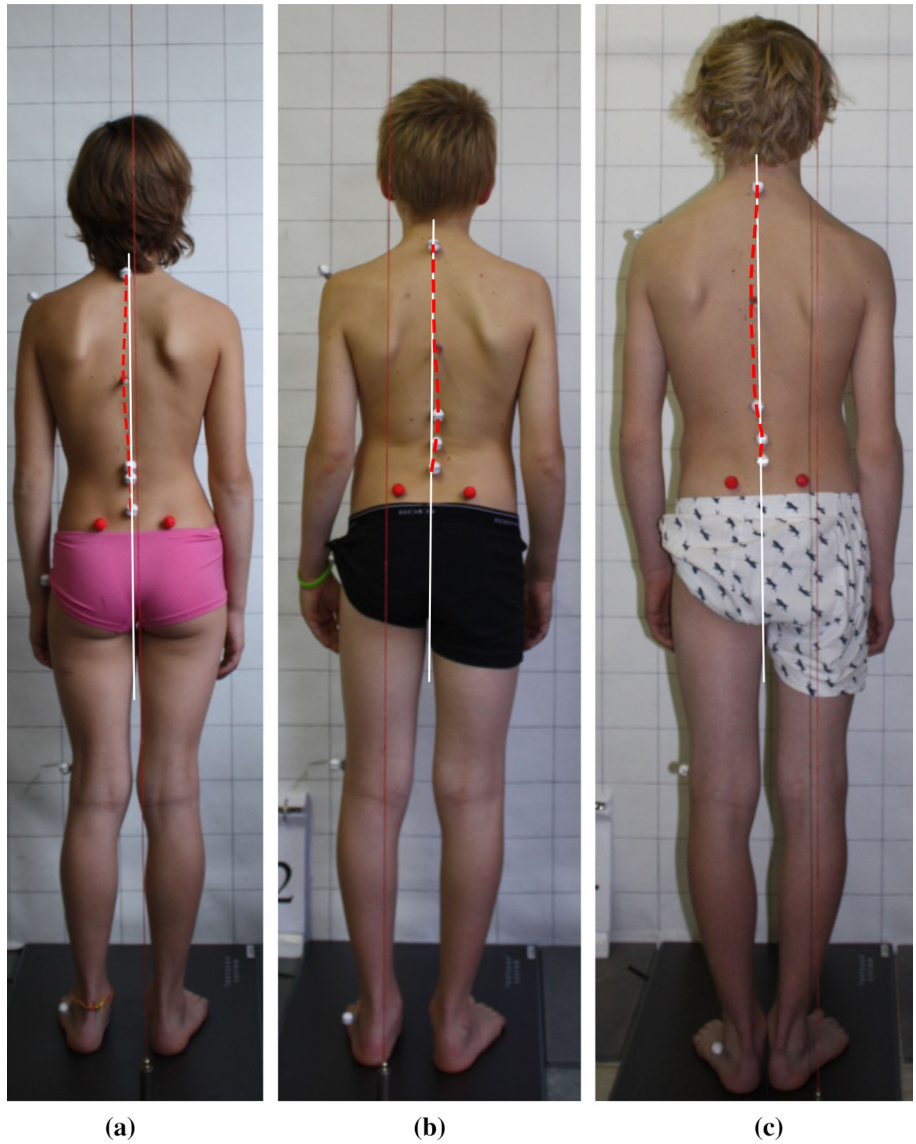

Fig. 1 Postural analysis in posterior view of subjects standing in their usual, relaxed posture, equally balanced on both feet, arms by the sides and looking straight ahead. Note the spinous processes of C7–L5 marked on the skin with a pen and the reflective markers placed on bony landmarks before photography [13, 19]: spinous process of the 7th cervical vertebra, apex of the thoracic kyphosis, inflection point where the spine transitions from kyphosis to lordosis, apex of the lumbar lordosis, spinous process of the 5th lumbar vertebra, posterior superior iliac spines. When a visually observed asymmetry of the trunk was present, the area of coronal asymmetry was determined as follows: **a** primary thoracic curve, **b** primary (thoraco)lumbar curve, **c** double [thoracic and (thoraco)lumbar] curve. The side of trunk asymmetry was defined by the *line* of spinous processes with respect to the central sacral *vertical line*

Sagittal plane posture was analyzed using commonly used parameters to investigate sagittal spinopelvic alignment [4, 6–8, 20]. In addition, a previously validated classification system for categorization of sagittal postural alignment in the standing position was used for further describing overall sagittal profile [21–24], implying that each subject was classified as having a “neutral-type”, “sway-back type” or “leaning-forward type” sagittal alignment of the body in the upright position. A list of the nomenclature for all sagittal parameters with their descriptions is provided in Table 1. Figure 2 illustrates the clustering method for global body alignment as applied previously to this study cohort [21, 22]. Further detail on the procedures for data collection can be found elsewhere [13, 19, 21], including information concerning reliability and validity of the sagittal postural measures used.

Body height and the proportion of trunk to body length were determined using a standardized procedure [13–15]. Body mass index (BMI) was calculated as the ratio of weight to square height and was transformed into three categories (thin, normal, and overweight or obese) using the cut-off points for age and gender defined by Cole et al. [25, 26]. To assess generalized joint laxity, the Beighton score was determined. A participant was classified as hypermobile when a Beighton score of ≥4/9 was obtained [27]. Self-reported handedness was recorded.

Statistical analysis

For comparative tests and proportions, the χ^2 test was used. Multivariate logistic regression was carried out for boys and girls, separately, to assess the independent association

Table 1 Nomenclature and descriptions of body posture parameters in the sagittal plane (standing position)

Parameter	Description
Global body alignment[a]	
Overall posture class	Postural subgroups (3 possible categories) based on the overall sagittal profile as determined by objective categorization procedure [21, 22]: (1) "Neutral global alignment", characterized by a small trunk lean angle (i.e., limited tilt of the trunk with respect to the vertical), a small pelvic displacement angle (i.e., little forward translation of the pelvis over the base of support as measured at the ankle), and an intermediate body lean angle that is close to 0 (i.e., the vertical projection of the C7 spinous process is close to the lateral malleolus). (2) "Sway-back", characterized by a large trunk lean angle (i.e., backward trunk lean relative to the hips), an intermediate pelvic displacement angle (i.e., slight forward carriage of the pelvis relative to the base of support), and a large (positive) body lean angle (i.e., the C7 spinous process plumbline passes well behind the lateral malleolus). (3) "Leaning-forward", characterized by an intermediate trunk lean angle (i.e., slight backward trunk lean), a large pelvic displacement angle (i.e., marked forward carriage of the pelvis relative to the feet), and a small (negative) body lean angle (i.e., the vertical projection of the C7 spinous process is anterior to the lateral malleolus)
Trunk lean angle (°)	Angle subtended between the vertical and a line joining C7 to the greater trochanter
Spinal-pelvic characteristics[b]	
Thoracic kyphosis (°)[c]	Sum of segmental angles of appropriate vertebral sections with the "thoracic" segment of the spine located between the C7–T1 interspace and the inflection point where the spine transitions from kyphosis to lordosis; positive when in kyphosis
Lumbar lordosis (°)[c]	Sum of segmental angles of appropriate vertebral sections with the "lumbar" segment of the spine located between the inflection point and the L5–S1 interspace; negative when in lordosis
Length of the posteriorly inclined spinal segment (# of vertebrae)[d]	Number of vertebrae included in the backwardly inclined segment (declive segment) between the apices of the thoracic and lumbar curves
Sacral inclination (°)[c]	Sacral angle with respect to the vertical; positive when tilted forward with respect to vertical line

[a] See Fig. 2 for illustration. Gross body segment orientations with respect to the vertical gravity vector were quantified post hoc on digital images using ImageJ software (National Institutes of Health, Bethesda, MD)

[b] See Online Resource 3 for illustration of the parameters, obtained (real-time) through direct postural assessment

[c] Obtained by the Spinal Mouse (Idiag; Voletswil, Switzerland), a hand-held, skin-surface, computer-assisted electromechanical-based device

[d] Determined via visual inspection and palpation

between the presence/absence of TA and its potential associated factors. A slimmed-down logistic regression model containing five predictors (trunk lean angle, thoracic kyphosis, number of vertebrae included in the declive thoracolumbar segment, sacral inclination, BMI) was built to focus on factors associated with TA within each of the three sagittal plane posture clusters. All reported p values are two-tailed, and are considered significant when less than 0.05. Analyses were executed with SPSS 22.0 for Windows (SPSS Inc., Chicago, IL, USA).

Missing values were not addressed in any particular way, thus leaving a total of 1190 participants included in analyses.

Results

Description of the study population

Predicted years from PHV, calculated using gender-specific predictive equations [15], were 1.2 ± 0.7 and 1.2 ± 0.6 years before pubertal peak growth in the male and female subjects, respectively. A total of 93.6% of the boys and 96.2% of the girls were classified as pre-PHV.

Coronal plane TA was present in 250 (21.0%) of the 1190 subjects. More specifically, TA was observed in 74/489 (15.1%) of those subjects categorized as sagittal neutral-type, 96/326 (29.4%) of leaning-forwards, and in 80/375 (21.3%) of subjects with a sway-back posture. There were no differences in the prevalence of TA between males and females, neither in the entire cohort, nor in the sagittal postural categories (Online Resource 1).

The proportions of curve location and the direction of the curve (left vs. right) for each type of coronal TA is tabulated in Online Resource 2, taking into consideration the sex of the child.

Factors associated with coronal plane TA

The results of unadjusted and adjusted effects of overall sagittal alignment on the prevalence of coronal plane TA

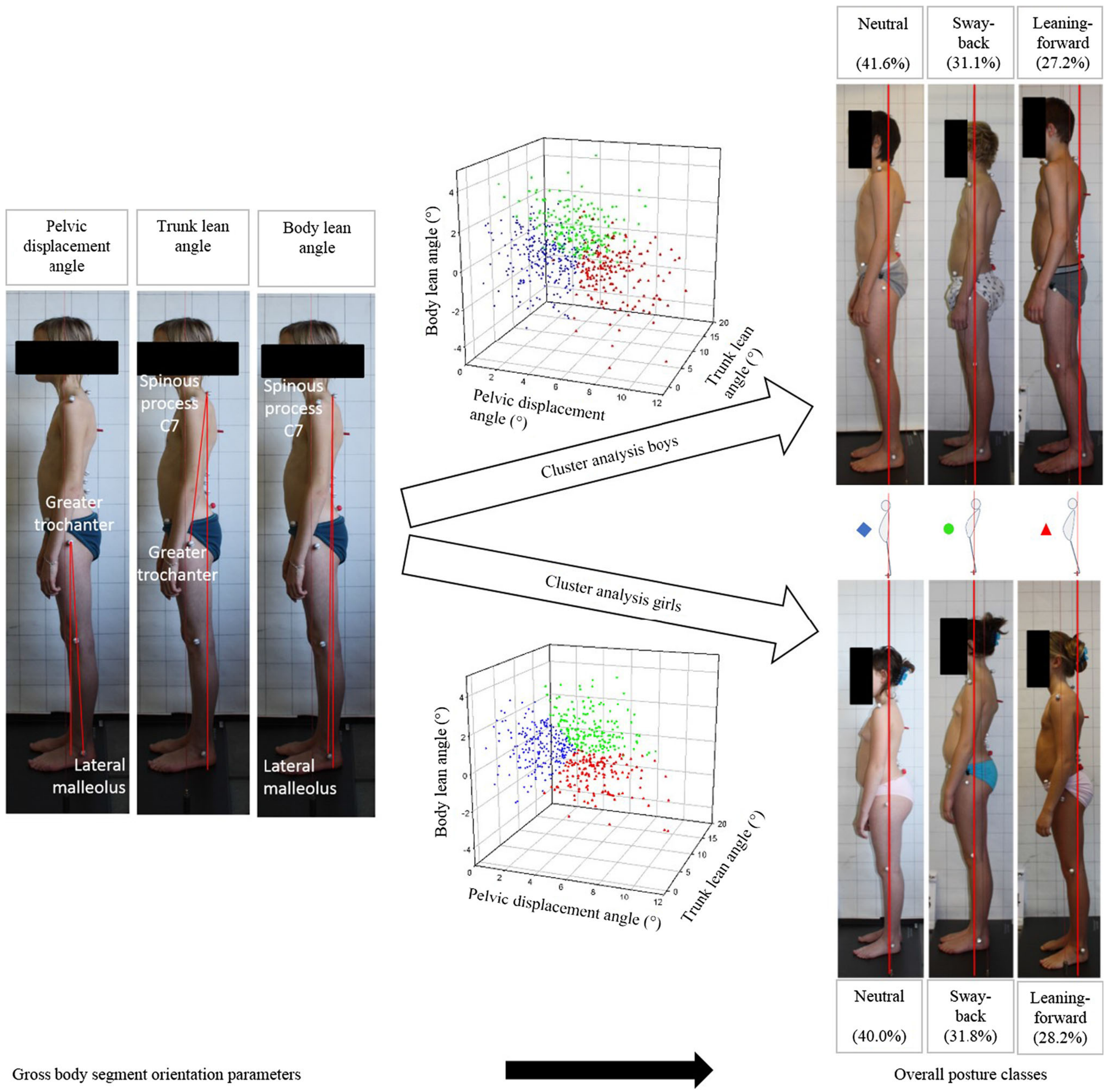

Fig. 2 Schematic illustration of the whole-body postural categorization of subjects before pubertal peak growth. The 3-dimensional scatter plot of the global alignment categorization among pre-peak height velocity girls [22] and the figure displaying a typical male and female member from each postural cluster [23] are reprinted by permission of the publisher. Each point in the scatter plots corresponds to a subject, classified as either neutral (*blue rhombus*), sway-back (*green circle*), or leaning-forward (*red triangle*) using cluster analysis [21, 22]

are presented in Table 2. In multivariate regression with adjustment for other factors, having a leaning-forward posture associated with a nearly three times higher odds of TA as compared with neutral overall posture in the sagittal plane. In boys, a sway-back compared with a neutral was 2.2 times more likely to show spinal and TA. A significant independent association of trunk lean in habitual standing with coronal plane TA was also found in boys, with an increase of 1° backward trunk lean being associated with an 11% decrease in odds of visually observed asymmetry of the trunk. In girls, the BMI significantly associated with coronal plane TA: overweight or obese subjects face a substantial (58%) decrease in the odds for TA compared to normal weight subjects ($p = 0.04$), whereas thinness tended to increase the odds of coronal TA although statistical significance was not reached ($p = 0.06$).

Table 2 Association between whole-body sagittal alignment and coronal plane trunk asymmetry with and without adjustment for potential confounders in boys and girls before pubertal peak growth

	Boys (n = 633) TA/no TA: 143/490			Girls (n = 557) TA/no TA: 107/450		
	OR	95% CI	p	OR	95% CI	p
Unadjusted						
Overall posture class			**0.027**			**<0.001**
Leaning-forward vs. neutral	1.86	1.18–2.94	**0.008**	3.18	1.87–5.39	**<0.001**
Sway-back vs. neutral	1.45	0.92–2.29	0.107	1.66	0.96–2.89	0.072
Adjusted[a]						
Overall posture class			**0.003**			**0.001**
Leaning-forward vs. neutral	2.69	1.52–4.76	**<0.001**	2.81	1.58–5.01	**<0.001**
Sway-back vs. neutral	2.22	1.16–4.23	**0.016**	1.39	0.61–3.20	0.435
Trunk lean angle	0.89	0.80–0.99	**0.025**	1.05	0.91–1.21	0.523
Length of the posteriorly inclined spinal segment	1.19	0.94–1.49	0.143	1.02	0.80–1.30	0.887
Thoracic kyphosis	1.00	0.97–1.02	0.803	1.01	0.98–1.04	0.746
Lumbar lordosis	0.95	0.91–1.01	0.084	0.97	0.91–1.03	0.307
Sacral inclination	0.95	0.89–1.01	0.112	0.98	0.91–1.06	0.601
Body height	1.01	0.99–1.04	0.365	1.02	0.99–1.06	0.243
Proportion of trunk length to body height	0.97	0.81–1.17	0.748	1.02	0.84–1.24	0.832
Body mass index			0.286			**0.015**
Thinness vs. normal	1.15	0.62–2.13	0.661	1.79	0.97–3.31	0.064
Overweight/obese vs. normal	0.59	0.30–1.18	0.135	0.42	0.18–0.94	**0.036**
Generalized joint laxity	0.68	0.36–1.32	0.255	0.89	0.50–1.57	0.674
Hand dominance	1.17	0.69–1.99	0.559	1.29	0.68–2.45	0.442

Bold p values—significant at $\alpha < 0.05$

CI confidence interval, *OR* odds ratio, *TA* trunk asymmetry

[a] In boys: Hosmer and Lemeshow: $\chi^2 = 4.15$, df 8, $p = 0.84$; in girls: Hosmer and Lemeshow: $\chi^2 = 5.14$, df 8, $p = 0.74$

The results obtained in boys do not make sense from the clinical point of view: neutrals, having less backward trunk inclination compared to leaning-forwards and sway-backs [21], had the lowest probability of having coronal plane TA while an independent association between less backward/more forward trunk lean and (higher odds of) coronal TA was found. Therefore, it was decided to (re)build a multivariate logistic regression model within each cluster of sagittal postural alignment, thereby taking into account the importance of events per variable in logistic regression [28].

Factors associated with coronal plane TA in neutral, leaning-forward and sway-back subjects (Table 3)

Within the neutral global alignment cluster, multivariate logistic regression revealed a significant independent association between the trunk lean angle (sagittal plane) and coronal TA in boys: more forward trunk lean was associated with an increase in odds of TA [odds ratio (OR) 0.82; 95% confidence interval (CI) 0.70–0.96; $p = 0.011$]. In girls classified as having a neutral sagittal overall alignment, having high levels of thoracic kyphosis was associated with an increase in odds of TA (OR 1.04; 95% CI 1.00–1.09; $p = 0.043$).

In leaning-forward girls, the adjusted odds of TA was nearly three times higher in thin subjects than in normal weight subjects (OR 2.95; 95% CI 1.16–7.51; $p = 0.023$).

In sway-back girls, a significantly higher odds of TA was shown for having backward trunk lean in customary standing, with an increase of 1° backward trunk lean being associated with a 32% increase in odds of coronal TA (OR 1.32; 95% CI 1.01–1.72; $p = 0.042$).

Association between whole-body sagittal alignment and type of coronal plane TA

Shown in Table 4 are the count and percentage of subjects per sagittal posture type for each coronal curve type. The χ^2 statistic revealed a significant association between overall posture class (sagittal plane) and the area of spinal and TA [$\chi^2(4, n = 250) = 30.55$, $p < 0.001$]. Within the 46 individuals determined to have (primary) thoracic coronal asymmetry, sway-back subjects were

Table 3 Factors potentially associated with coronal plane trunk asymmetry in healthy boys and girls classified as having neutral, leaning-forward or sway-back overall alignment

	Neutral overall alignment ($n = 489$)						Leaning-forward posture ($n = 326$)						Sway-back posture ($n = 375$)					
	Boys ($n = 265$) TA/no TA: 47/218			Girls ($n = 224$) TA/no TA: 27/197			Boys ($n = 171$) TA/no TA: 49/122			Girls ($n = 155$) TA/no TA: 47/108			Boys ($n = 197$) TA/no TA: 47/150			Girls ($n = 178$) TA/no TA: 33/145		
	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*	OR	95% CI	*p*
Trunk lean angle	0.82	0.70–0.96	**0.011**	0.86	0.69–1.08	0.202	1.04	0.88–1.24	0.626	1.12	0.91–1.38	0.280	0.88	0.73–1.05	0.152	1.32	1.01–1.72	**0.042**
Length of the posteriorly inclined spinal segment	1.27	0.89–1.82	0.185	0.86	0.59–1.26	0.448	1.19	0.79–1.80	0.409	1.04	0.67–1.61	0.868	1.00	0.67–1.47	0.986	1.09	0.71–1.67	0.704
Thoracic kyphosis	1.01	0.97–1.04	0.785	1.04	1.00–1.09	**0.043**	0.99	0.95–1.03	0.590	1.02	0.99–1.06	0.236	1.02	0.99–1.06	0.169	1.01	0.97–1.05	0.780
Sacral inclination	1.01	0.96–1.07	0.626	1.02	0.95–1.10	0.622	0.99	0.93–1.05	0.764	1.03	0.96–1.10	0.459	0.99	0.93–1.05	0.717	1.02	0.95–1.09	0.596
Body mass index			0.638			0.684			0.307			**0.014**			0.236			0.153
Thinness vs. normal	1.05	0.47–2.33	0.908	0.72	0.23–2.29	0.576	0.45	0.12–1.68	0.233	2.95	1.16–7.51	**0.023**	1.68	0.61–4.65	0.319	1.82	0.57–5.87	0.314
Overweight/obese vs. normal	0.49	0.10–2.26	0.357	0.55	0.11–2.71	0.464	0.49	0.13–1.86	0.293	0.16	0.02–1.33	0.091	0.57	0.23–1.45	0.237	0.45	0.15–1.30	0.138
	Hosmer and Lemeshow						Hosmer and Lemeshow						Hosmer and Lemeshow					
	$\chi^2 = 5.94$, *df* 8, $p = 0.65$			$\chi^2 = 1.32$, *df* 8, $p = 1.00$			$\chi^2 = 6.96$, *df* 8, $p = 0.54$			$\chi^2 = 8.81$, *df* 8, $p = 0.36$			$\chi^2 = 6.05$, *df* 8, $p = 0.64$			$\chi^2 = 4.64$, *df* 8, $p = 0.80$		

CI confidence interval, *OR* odds ratio, *TA* trunk asymmetry

Bold *p* values—significant at $\alpha < 0.05$

proportionally least represented. In the subset with a primary curve in the lumbar and/or declive thoracolumbar segment, sway-back was the most common type of sagittal plane posture.

From leaning-forward subjects with a coronal asymmetry of the trunk, 61.5% (59/96) of cases had a combined thoracic and lumbar curve while 31.3% (30/96) had a primary thoracic curve. In neutral type subjects with a TA in the coronal plane, a double thoracic and lumbar curve and primary thoracic curve was present in 73.0% (54/74) and 18.9% (14/74) of cases, respectively.

Discussion

This study reports the results of the first population-based study designed to investigate coronal plane TA and its association with sagittal standing posture in boys and girls without known scoliosis, at pre-PHV age. The most important finding of this work is that coronal plane TA is seen more frequently in non-neutral than in neutral overall sagittal profiles. Compared with neutrals, leaning-forwards are nearly three times more likely to show coronal plane TA on the eve of pubertal peak growth; Sway-backs are more than twice as likely to have TA than neutrals, but only among boys. In non-neutral sagittal configurations (see Table 1), the rotational stability of the spine could be suspected to be thoroughly challenged, because of the load on the posterior parts of the vertebral column and/or the posterior shear loads affecting the posteriorly inclined segments [7–10, 29].

Table 4 Count and percentage of subjects with neutral, leaning-forward and sway-back sagittal alignment for the three coronal curve types ($n = 250$)

	Overall posture class			Total
	Neutral	Leaning-forward	Sway-back	
Coronal curve location				
Primary thoracic curve				
Count	14_a	30_a	2_b	46
%	30.4	65.2	4.3	100.0
Primary (thoraco)lumbar curve				
Count	6_a	7_a	17_b	30
%	20.0	23.3	56.7	100.0
Double [thoracic and (thoraco)lumbar] curve				
Count	54_a	59_a	61_a	174
%	31.0	33.9	35.1	100.0
Total				
Count	74	96	80	250
%	29.6	38.4	32.0	100.0

Each subscript letter denotes a subset of overall posture categories whose column proportions do not differ significantly from each other at the 0.05 level by χ^2. See Figs. 1, 2 and Table 1 for descriptions of parameters

Associations of BMI, sagittal plane trunk inclination and thoracic kyphosis with coronal plane TA are also shown by the present study. These associations, however, appear to be gender and posture class specific. More specifically, the current results convey an increased likelihood of TA with (1) thinness, in the female leaning-forward subset, (2) more backward trunk inclination, in the female sway-back subset, (3) more forward trunk inclination, in boys with a neutral overall sagittal alignment, and (4) increasing thoracic kyphosis, in girls with a neutral overall sagittal posture. Although, evidently, questions regarding the etiopathogenesis of AIS cannot be answered by this cross-sectional study, it is interesting to speculate about how postural features at pre-PHV age might contribute to “the perfect storm” of scoliosis establishment or progression during pubertal peak growth.

Thus far, there has been very little study to discover whether some type of postural configuration existing in the immature non-scoliotic spine would have any value in predicting the development of AIS. The notable exception is a prospective study of Finnish prepubertal schoolchildren who were free from scoliosis at entry [4]. In that work, TA was identified as a predictor of future scoliosis [4], suggesting that an initial coronal plane TA could be of paramount importance in the biomechanical mechanism yielding curve progression. Using a spinal pantograph to assess sagittal spinal profiles, Nissinen et al. [4] further found that AIS was predicted by an increased thoracic kyphosis (only in girls) and an increased lumbar lordosis (only in boys) at the prepubertal stage. At first sight, these latter findings differ from biomechanical theories on the etiology of AIS [7–10, 29] and hardly fit clinical insights and earlier studies on (progressive) AIS [30]. Crucial for understanding the true biomechanical challenges that are posed to the spinal-pelvic complex, however, is that spinal-pelvic measurements alone may not be sufficient to characterize spinal-pelvic loading. Otherwise put, the meaning of a certain value of a sagittal spinopelvic parameter (being thoracic kyphosis, sagittal trunk inclination, lumbar lordosis, or other)—whether or not in the presence of TA—may vary according to the overall sagittal posture class one belongs to (i.e., neutral, sway-back or leaning-forward). What we suggest here, is that whole-body sagittal alignment might have been systematically overlooked in research related to initiation, progression and management of AIS. The importance of moving beyond analysis of data aggregated across sagittal whole-body posture types has recently proven very useful for gaining insights into gender differences in sagittal plane posture at pre-PHV age [23]. Although the context and research question was different, the same line of reasoning might apply.

Interestingly, the current results reveal for the first time that the spinal region where TA is observed differs according to whole-body sagittal alignment type. As an example, 65.2% of those subjects with a primary thoracic curve were classified as having a leaning-forward posture while only 4.3% were sway-backs. Primary curves in the declive thoracolumbar region and/or lumbar spine, on the other hand, were significantly more prevalent in sway-backs than in neutrals or leaning-forwards. The concept that different types of AIS probably develop in different sagittal profiles is not new [20, 31]. The present study, however, is the first that considers truncal asymmetry types in relation to sagittal plane posture in healthy young adolescents without known scoliosis, thereby starting from a whole-body sagittal posture perspective.

Additionally, our data provide further support for the view that the direction of the deformity in AIS is determined by the rotational pattern present in the normal spine [11, 32]. Indeed, the pattern of deviation of the palpated spinous process line with respect to the central sacral vertical line observed here (see Online Resource 2) agrees with the pattern of vertebral rotation in the transverse plane that has previously been established in the normal adolescent and adult spine using computed tomographic scans [11, 33] and matches the rotation of the curve as is predominantly seen in AIS [34].

Several limitations should be acknowledged. The main limitation of this work is its cross-sectional nature at this phase which restricts us from drawing any conclusions regarding temporal or causal relationships between sagittal and coronal plane posture. Long period observational follow-up is needed to fully appreciate how the initiation and progression of AIS could be related to baseline postural characteristics. Revealing an AIS risk profile, where prepubertal posture may play a role among other factors, provides the framework for (1) early identification of those individuals at sufficiently increased risk of progressive AIS, and (2) targeted risk factor management. In such research, it would be of great interest to extend posture analysis to posture and movement analysis [35]. Another concern in this study is that we cannot claim that all participants are free from scoliosis (i.e., Cobb angle $<10°$) as no radiographs were taken. Neither can we claim that none of the participants was already at or past his/her PHV at the time of assessment. To define the children's phase of growth, growth velocity was not measured as this would have required serial data surrounding the occurrence of peak. Instead, PHV occurrence was predicted using gender-specific multiple regression equations that take into consideration the differential timing of the adolescent spurt in body dimensions and their interactions with chronological age [15]. Nevertheless, we strongly believe that—at the group level—our study population can be considered representative of healthy non-scoliotic subjects before pubertal peak growth. Third, the fact that subjects were not screened with Adam's forward bend test and a scoliometer may be argued upon. However, the small curves that were usually detected in this study might not lend themselves well to scoliometer examination and, as Bunnell [36] and others have shown, rib asymmetry does not always equate with vertebral column asymmetry. On the other hand, based on recent research by Schmid et al. [37] in patients with AIS, spinous process-derived evaluations of coronal plane posture may be suspected to underestimate the curvature formed by the vertebral body in the frontal plane.

Conclusions

This study demonstrates that whole-body sagittal alignment differs between healthy immature subjects with vs. without coronal plane TA. Having a leaning-forward posture, in particular, associates with increased odds of having TA. The lowest odds ratio is for neutrals. Furthermore, significant associations with coronal plane TA are found for trunk lean, thoracic kyphosis and BMI. These correlations, however, are gender and posture class specific. The spinal region where rotational stability is challenged, appears to vary according to the whole-body sagittal alignment type. These data support the hypothesis that a certain biomechanical loading of the spinopelvic complex in the sagittal plane may predispose a child to the development of a deformity in the other planes, in other words AIS. Nevertheless, temporal or causal relationships between sagittal and coronal plane posture cannot be derived from this study. Longitudinal follow-up is warranted to identify risk factors for (progressive) AIS needing treatment.

Acknowledgements We are indebted to the pupils, parents and staff of the schools and pupil guidance centers for taking part in this study.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest. The authors had full control of all primary data. The authors agree to allow the journal to review our data if requested.

References

1. Weinstein SL, Dolan LA, Cheng JC et al (2008) Adolescent idiopathic scoliosis. Lancet 371:1527–1537
2. Stokes IAF (1994) Three-dimensional terminology of spinal deformity. A report presented to the Scoliosis Research Society by the Scoliosis Research Society Working Group on 3-D terminology of spinal deformity. Spine 19:236–248

3. Lonstein JE (2006) Scoliosis: surgical versus nonsurgical treatment. Clin Orthop Relat Res 443:248–259
4. Nissinen MJ, Heliövaara MM, Seitsamo JT, Poussa MS (1993) Trunk asymmetry, posture, growth, and risk of scoliosis. A 3-year follow-up of Finnish prepubertal school children. Spine 18:8–13
5. Nissinen MJ, Heliövaara MM, Seitsamo JT et al (2000) Development of trunk asymmetry in a cohort of children ages 11–22 years. Spine 25:570–574
6. Dickson RA (1988) The aetiology of spinal deformities. Lancet 1:1151–1155
7. Kouwenhoven JW, Smit TH, van der Veen AJ et al (2007) Effects of dorsal versus ventral shear loads on the rotational stability of the thoracic spine: a biomechanical porcine and human cadaveric study. Spine 32:2545–2550
8. Castelein RM, van Dieën JH, Smit TH (2005) The role of dorsal shear forces in the pathogenesis of adolescent idiopathic scoliosis—a hypothesis. Med Hypotheses 65:501–508
9. Castelein RM, Veraart B (1992) Idiopathic scoliosis: prognostic value of the profile. Eur Spine J 1:167–169
10. Janssen MM, Kouwenhoven JW, Castelein RM (2010) The role of posteriorly directed shear loads acting on a pre-rotated growing spine: a hypothesis on the pathogenesis of idiopathic scoliosis. Stud Health Technol Inform 158:112–117
11. Janssen MM, Kouwenhoven JW, Schlosser TP et al (2011) Analysis of preexistent vertebral rotation in the normal infantile, juvenile, and adolescent spine. Spine 36:E486–E491
12. Vercauteren M, Van Beneden M, Verplaetse R et al (1982) Trunk asymmetries in a Belgian school population. Spine 7:555–562
13. Dolphens M, Cagnie B, Coorevits P et al (2012) Sagittal standing posture and its association with spinal pain: a school-based epidemiological study of 1196 Flemish adolescents before age at peak height velocity. Spine 37:1657–1666
14. Dolphens M, Vansteelandt S, Cagnie B et al (2016) Multivariable modeling of factors associated with spinal pain in young adolescence. Eur Spine J 25:2809–2821
15. Mirwald RL, Baxter-Jones AD, Bailey DA et al (2002) An assessment of maturity from anthropometric measurements. Med Sci Sports Exerc 34:689–694
16. Tabard-Fougère A, Bonnefoy-Mazure A, Hanquinet S et al (2017) Validity and reliability of spine rasterstereography in patients with adolescent idiopathic scoliosis. Spine 42:98–105
17. Schroeder J, Reer R, Braumann KM (2014) Video raster stereography back shape reconstruction: a reliability study for sagittal, frontal, and transversal plane parameters. Eur Spine J 24:262–269
18. Guidetti L, Bonavolontà V, Tito A et al (2013) Intra- and interday reliability of spine rasterstereography. Biomed Res Int 1:745480
19. Dolphens M, Cagnie B, Vleeming A et al (2012) A clinical postural model of sagittal alignment in young adolescents before age at peak height velocity. Eur Spine J 21:2188–2197
20. Schlösser TP, Shah SA, Reichard SJ et al (2014) Differences in early sagittal plane alignment between thoracic and lumbar adolescent idiopathic scoliosis. Spine J 14:282–290
21. Dolphens M, Cagnie B, Coorevits P et al (2013) Classification system of the normal variation in sagittal standing plane alignment: a study among young adolescent boys. Spine 38:E1003–E1012
22. Dolphens M, Cagnie B, Coorevits P et al (2014) Classification system of the sagittal standing alignment in young adolescent girls. Eur Spine J 23:216–225
23. Dolphens M, Cagnie B, Vleeming A et al (2013) Gender differences in sagittal standing alignment before pubertal peak growth: the importance of subclassification and implications for spinopelvic loading. J Anat 223:629–640
24. Dolphens M, Cagnie B, Coorevits P et al (2014) Posture class prediction of pre-peak height velocity subjects according to gross body segment orientations using linear discriminant analysis. Eur Spine J 23:530–535
25. Cole TJ, Bellizzi MC, Flegal KM et al (2000) Establishing a standard definition for child overweight and obesity worldwide: international survey. BMJ 320:1240–1243
26. Cole TJ, Flegal KM, Nicholls D et al (2007) Body mass index cut offs to define thinness in children and adolescents: international survey. BMJ 335:194
27. Beighton PH, Grahame R, Bird HA (1999) Hypermobility of joints. Springer, London
28. Peduzzi P, Concato J, Kemper E et al (1996) A simulation study of the number of events per variable in logistic regression analysis. J Clin Epidemiol 49:1373–1379
29. Homminga J, Lehr AM, Meijer GJ et al (2013) Posteriorly directed shear loads and disc degeneration affect the torsional stiffness of spinal motion segments: a biomechanical modeling study. Spine 38:E1313–E1319
30. Nault ML, Mac-Thiong JM, Roy-Beaudry M et al (2014) Three-dimensional spinal morphology can differentiate between progressive and non-progressive patients with adolescent idiopathic scoliosis at the initial presentation. Spine 39:E601–E606
31. Mac-Thiong JM, Labelle H, Charlebois M et al (2003) Sagittal plane analysis of the spine and pelvis in adolescent idiopathic scoliosis according to the coronal curve type. Spine 28:1404–1409
32. Castelein RM (2012) Pre-existent rotation of the normal spine at different ages and its consequences for the scoliotic mechanism. Stud Health Technol Inform 176:20–25
33. Kouwenhoven JW, Vincken KL, Bartels LW et al (2006) Analysis of preexistent vertebral rotation in the normal spine. Spine 31:1467–1472
34. Hong JY, Suh SW, Easwar TR et al (2013) Clinical anatomy of vertebrae in scoliosis: global analysis in four different diseases by multiplanar reconstructive computed tomography. Spine J 13:1510–1520
35. Yang JH, Suh S-W, Sung PS, Park W-H (2013) Asymmetrical gait in adolescents with idiopathic scoliosis. Eur Spine J 22:2407–2413
36. Bunnell WP (1984) An objective criterion for scoliosis screening. J Bone Jt Surg Am 66:1381–1387
37. Schmid S, Studer D, Hasler CC et al (2015) Using skin markers for spinal curvature quantification in main thoracic adolescent idiopathic scoliosis: an explorative radiographic study. PLoS One 10:e0135689