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Coronal trunk imbalance in idiopathic scoliosis: Does gravity line localisation confirm the physical findings?

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A B S T R A C T

Background: Adolescent idiopathic scoliosis (AIS) can require surgical procedures that have major consequences. Coronal imbalance as assessed clinically using a plumb line is a key criterion for selecting patients to surgery. Nevertheless, the reference standard for assessing postural balance of the trunk is gravity line localisation within a validated frame of reference. Recent studies have established that the gravity line can be localised after body contour reconstruction from biplanar radiographs. The objective of this study was to validate a gravity line localisation method based on biplanar radiographs in a population with AIS then to validate gravity line position versus plumb line position.

Hypothesis: Plumb line and gravity line assessments of coronal balance correlate with each other.

Material and methods: A gravity line localisation method based on biplanar radiography was validated in 14 patients with AIS versus force platform as the method of reference. Normal plumb line and gravity line positions were determined in 27 asymptomatic adolescents using biplanar radiography. The results of the two methods were then compared in 53 patients with AIS.

Results: The reliability of gravity line localisation in the coronal plane based on biplanar radiography was 2.4 mm (95% confidence interval). The distance between the gravity line and the middle of the line connecting the centres of the two femoral heads (HA) showed a strongly significant association with plumb line position computed as the distance from the vertical line through the middle of T1 and the centre of the S1 endplate (T1V/S): $r = 0.71, p < 0.0001$. Of the 20 patients with plumb line results indicating coronal imbalance, 11 (55%) had a normal gravity line-to-HA distance. Of the 33 patients with normal plumb line results, 7 (21%) had an abnormal gravity line-to-HA distance.

Conclusion: The results of this study validate gravity line determination from biplanar radiographs in a population with AIS. Plumb line position correlated significantly with gravity line position but was less accurate for guiding surgical decisions.

Level of evidence: IV, retrospective study.

Keywords:

Adolescent idiopathic scoliosis, Gravity line localisation, Coronal trunk imbalance, Biplanar radiography

Introduction

Adolescent idiopathic scoliosis (AIS) is a common condition that affects about 3% of all adolescents [1]. Early detection followed by appropriate treatment decreases the need for surgery and the risk of complications in adulthood (e.g., low back pain, degenerative disc disease, and respiratory insufficiency). The main criterion used

to determine whether surgery is appropriate in a patient with AIS is Cobb's angle (usually with a cut-off of 40°) [1]. Coronal trunk imbalance as assessed using the plumb line method is associated with curve progression, even in adults, and may therefore support surgical treatment [2,3]. In recent studies of overall trunk posture, a force platform was used to localise the gravity line [4–6]. Gravity line position correlated with quality of life and self-esteem in a population of adults with scoliosis [7]. Gravity line position can also be determined by body contour reconstruction from low-dose biplanar radiographs, as recently reported in healthy individuals [8,9].

The decision to perform scoliosis surgery can have major anatomic, functional, and psychological consequences. Complications are dominated by mechanical and infectious events and still occur in as many as 6% of patients [10]. Surgical decisions must therefore be based on objective criteria assessed using reliable tools that are accurate and impose as few constraints as possible on the patient and surgeon. Objectively and accurately assessing coronal trunk balance by gravity line localisation based on biplanar radiographs may hold promise as an aid to treatment decision-making.

The objective of this study was to validate a gravity line localisation method based on biplanar radiographs in a population with AIS then to validate gravity line position versus plumb line position as a measure of coronal trunk balance. In addition, gravity line position was evaluated in each of the anatomic types of scoliosis present in our population. The working hypothesis was that plumb line and gravity line assessments of coronal balance correlated with each other.

2. Material and methods

The gravity line localisation method was validated in 14 prospectively recruited patients receiving follow-up for AIS. The patients were all under 18 years of age. Our institutional review board approved the study, and informed consent to study participation was obtained from the patients and/or parents.

Biplanar radiographs were obtained using the EOS system (EOS-Imaging, Paris, France), with the patient standing on a force platform (Wii Balance Board, Nintendo France, Cergy-Pontoise, France) according to a previously validated protocol [11]. The gravity line of reference was determined based on the mean position of the reaction forces from the force platform during image acquisition. Body contour reconstruction was performed using a method previously validated in healthy individuals [9]. For body contour reconstruction, the contour of a 3D template was back-projected onto the antero-posterior and lateral radiographic views. An operator could adjust the back-projected contour to match the body contour of the patient (Fig. 1). The biplanar radiograph gravity line was defined as the vertical line through the whole-body centre of mass (WBCM) and was compared to the reference gravity line identified by the force platform. The masses obtained using the two methods were also compared.

Correlations between plumb line position and gravity line position were then assessed in 27 apparently healthy individuals (controls) defined as having only minimal spinal deformity with a Cobb's angle of less than 10° and in 53 patients with documented AIS and a Cobb's angle greater than 10° . Individuals with congenital spinal abnormalities or other types of spinal deformity (e.g., spondylolisthesis) were excluded. Standing whole-body biplanar radiographs were acquired in each study participant according to the same protocol [12].

A patient-specific 3D model of the entire spine (from the dens to S1), pelvis, and body contour was obtained using previously reported reconstruction methods [8,13,14] (Fig. 1). The normal range for plumb line position was defined based on the distance on the antero-posterior view in the control group between the vertical line through the centre of T1 and the centre of the S1 endplate (T1V/S) (Fig. 2). Coronal trunk imbalance in the patients was then defined as a T1V/S value above the 95th centile in the control group. Cobb's angle and the T1V/S distance were determined using the 3D reconstructions. In all patients, the gravity line was defined as the vertical line through the WBCM [8]. In each patient, the distances separating the gravity line in the coronal plane from the middle of the line connecting the centres of the two femoral heads HA (GL/HA) and the dens (GL/D) were compared to the T1V/S distance (Fig. 2). In the groups of patients with and without coronal trunk

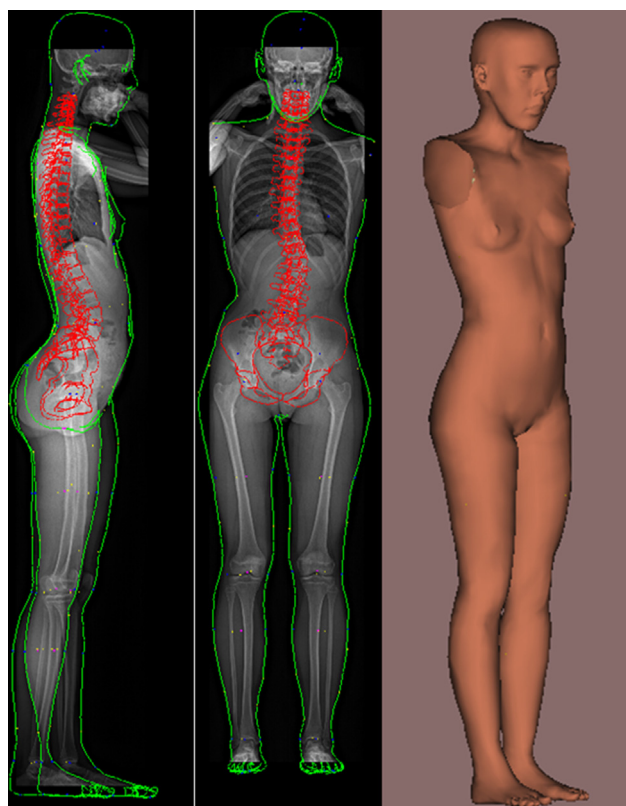


Fig. 1. 3D reconstruction of the spine and body contour.

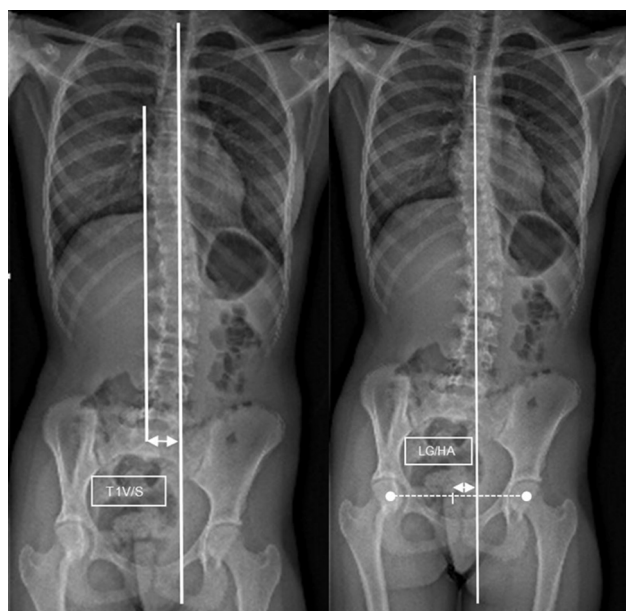


Fig. 2. Plumb line position (T1V/S) and gravity line position (GL/HA). T1V/S, distance between the vertical through the middle of T1 and the midpoint of the S1 endplate; GL, gravity line localised using biplanar radiographs; HA, midpoint of the line connecting the femoral heads; GL/HA, distance between the gravity line and HA.

imbalance and in the control group, we also assessed head position in the coronal plane as the position of the dens relative to the gravity line and the angle between the dens-HA line and the vertical from the dens [8].

Statistics: The statistical analysis was performed using SPSS V23.0 (IBM, Armonk, NY, USA). Values of p smaller than 0.05 were

taken to indicate significant differences. Gravity line position and body mass obtained using the two methods were compared by applying Student's *t*-test. The Lilliefors test was chosen to assess normality. The correlation between T1V/S and GL/HA was evaluated by computing Spearman's coefficient. The controls and the patients with thoracic, thoraco-lumbar, lumbar, and double major curves were compared using the Kruskal-Wallis test followed by Dunn's post hoc test given the non-normal data distribution.

3. Results

3.1. Validation of the gravity-line localisation method on biplanar radiographs

Validation was performed in 14 patients with AIS, 9 females and 5 males with a mean age of 14 years, a mean body weight of 51.9 ± 4.6 kg, and a mean major-curve Cobb's angle of $22 \pm 11^\circ$ (range, $10\text{--}55^\circ$).

The mean difference between the body mass values by force platform and 3D reconstruction was 0.8 ± 1.2 kg (range, -2.4 to $+1.9$ kg) (Table 1), which was not statistically significant ($p=0.14$). The mean difference in gravity-line position was 0.5 ± 1.2 mm in the coronal plane and 0.9 ± 3.1 mm in the sagittal plane; again, these differences were not significant ($p=0.3$ and $p=0.12$, respectively). The Bland and Altman plot indicated good agreement between the two methods (Fig. 3).

3.2. Comparison of plumb line and gravity line positions in patients and controls

The 27 controls without clinically relevant spinal deformities included 14 females and 13 males with a mean age of 13 years, mean body weight of 44.8 ± 9.7 kg, and mean T1V/S distance of -0.46 ± 9.1 mm.

The group of 53 patients with AIS was composed of 40 females and 13 males with a mean age of 14.4 years, a mean body weight of 50.6 ± 9.5 kg, and a mean Cobb's angle of $32 \pm 16^\circ$. Comparing the

Table 1
Validation of the biplanar radiograph method for gravity line positioning, using force platform as the reference standard.

Mean \pm SD	Δ Mass (Kg)	Δ X (mm) Sagittal	Δ Y (mm) Coronal
Present study	0.8 ± 1.2	0.9 ± 3.1	0.5 ± 1.2
Study by Amabile et al. (2016)	0.3 ± 1.9	0.7 ± 4.9	1.5 ± 1.9

Δ : difference.

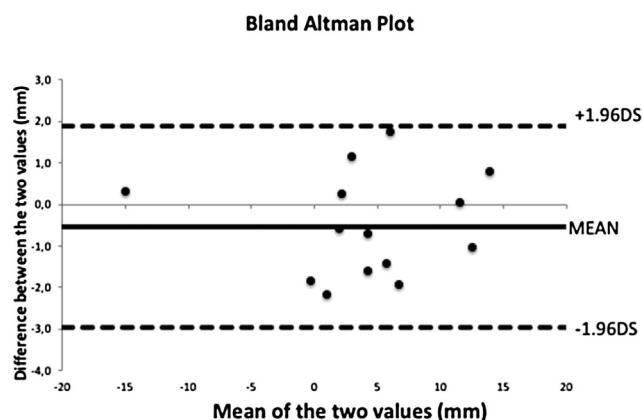


Fig. 3. Bland-Altman plot to assess agreement between gravity line position in the coronal plane determined using a force platform and using the biplanar radiograph method.

Table 2
Features of the controls and patient subgroups.

Subgroups	Number	BMI	Age (years)	Gender	Cobb's angle ($^\circ$)
Controls	27	18	13	14F 13M	0-9
Scoliosis, overall	53	19	14	40F 13M	32
Scoliosis, without imbalance	33	19	14	27F 6M	27
Scoliosis, with imbalance	20	19	14	13F 7M	39
Scoliosis, thoracic	16	19	14	10F 6M	31
Scoliosis, thoraco-lumbar	19	19	14	15F 4M	32
Scoliosis, lumbar	10	20	15	7F 3M	24
Scoliosis, double major	8	20	14	8F 0M	43

BMI: body mass index in kg/m^2 ; F: female; M: male.

T1V/S distance to the normal range indicated that 20 patients did and 33 did not have coronal trunk imbalance (Table 2).

The mean GL/HA distance was -1.3 ± 4.8 mm in the controls, 1.1 ± 6.8 mm in the patients without imbalance, and 7.2 ± 8.8 mm in the patients with imbalance. The T1V/S and GL/HA distances correlated closely to each other ($r=0.71$ and $p<0.0001$) (Fig. 4). However, comparing these distances in the patients to the normal ranges determined in the controls showed that 7 (21%) of the 33 patients whose T1V/S distance indicated no imbalance had a GL/HA distance outside the normal range. On the other hand, 11 (55%) of the 20 patients whose T1V/S distance indicated imbalance had a GL/HA distance within the normal range. The T1V/S distance was not significantly correlated with Cobb's angle or with the body mass index ($p=0.64$ and $p=0.11$, respectively) (Table 3).

3.3. Curve type subgroups

The GL/HA distance in the subgroups with thoraco-lumbar or lumbar scoliosis was greater (7.2 mm) than in the subgroup with thoracic scoliosis (-2.8 mm) and in the controls (-1.3 mm, $p<0.0001$, Kruskal-Wallis test). The values in the subgroup with double major curves were not significantly different from the values in the other subgroups ($p>0.05$) (Fig. 5).

3.4. Dens position

The mean distance between the dens and the gravity line was -3.8 ± 8.3 mm in the controls, -3.9 ± 9 mm in the patients with AIS and no coronal imbalance, and 6.0 ± 16.6 mm in the patients with AIS and coronal imbalance. The difference between the patients with imbalance and the other groups was significant ($p=0.009$) (Fig. 6), and 91% of patients without imbalance were within the normal range compared to only 40% of those with imbalance. In the coronal plane, the angle between the line from the dens to HA and the vertical was not significantly different across groups ($p=0.22$): $-0.4 \pm 0.8^\circ$ in controls, $-0.3 \pm 1^\circ$ in the patients without imbalance, and $0.1 \pm 1^\circ$ in the patients with imbalance.

Table 3
Correlations of plumb line position (T1V/S) with other parameters.

T1V/S	Spearman's coefficient (rho)	p-value
GL/HA	0.71	1×10^{-8}
Cobb's angle	0.065	0.64
BMI	0.178	0.11

T1V/S: distance between the vertical through the middle of T1 and the midpoint of the S1 endplate; GL: gravity line localised using biplanar radiographs; HA: midpoint of the line connecting the femoral heads; BMI: body mass index in kg/m^2 .

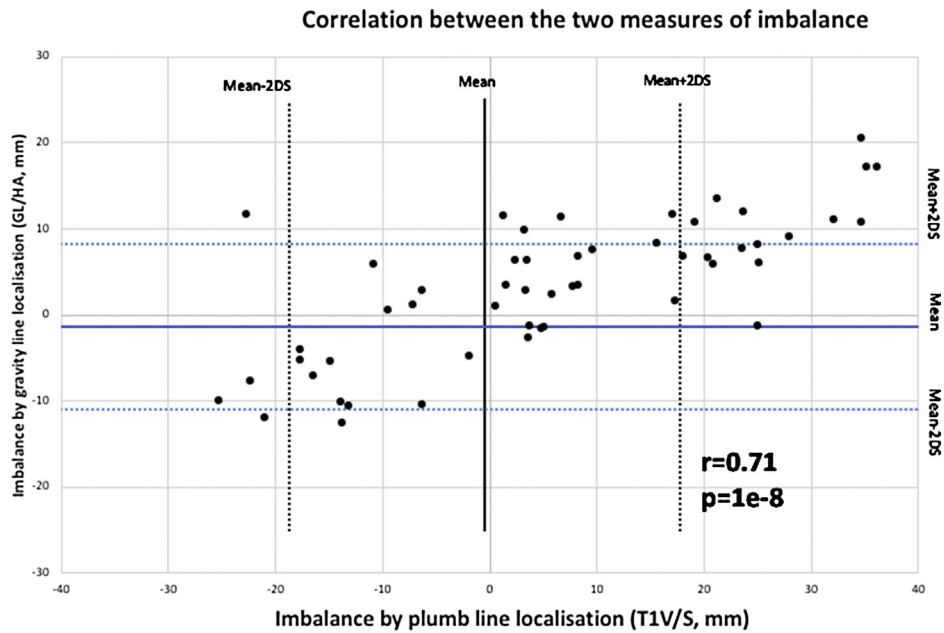


Fig. 4. Correlation between T1V/S and GL/HA in the population with scoliosis. The vertical and horizontal lines indicate the normal ranges determined in healthy controls. T1V/S, distance between the vertical through the middle of T1 and the midpoint of the S1 endplate; GL, gravity line localised using biplanar radiographs; HA, midpoint of the line connecting the femoral heads; GL/HA, distance between the gravity line and HA.

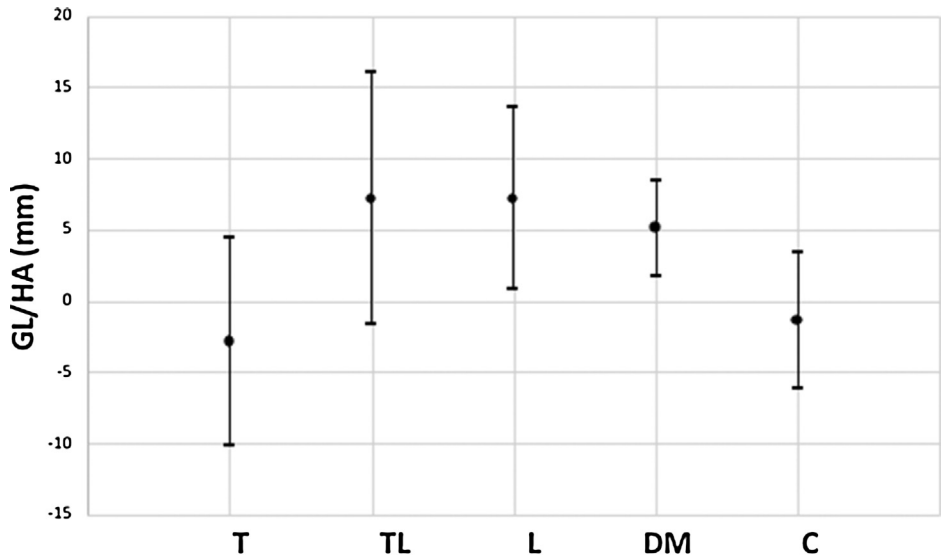


Fig. 5. Mean \pm SD values of the GL/HA distance in the subgroups defined by curve type. Note the significant differences between the thoraco-lumbar (TL) and lumbar (L) curves versus the thoracic curves (T) and healthy controls (C, $p = 4.5 \times 10^{-6}$, Kruskal-Wallis test). No significant differences were found between the double major curve subgroup and the other subgroups ($p > 0.05$).

4. Discussion

This study validated a new method for evaluating overall trunk balance in patients with AIS. Plumb line analysis is a clinical or radiographic method for assessing gravity line position to obtain accurate information on coronal trunk imbalance. The results may support the need for surgery to correct the spinal deformity. Objective gravity line localisation using a force platform is more accurate but ill-suited to everyday clinical practice. The increasing availability of biplanar radiograph systems such as EOS, which are becoming crucial to the evaluation and follow-up of patients with scoliosis, provides the opportunity to develop a gravity line localisation method based on biplanar radiography. One such method was developed by the graduate engineering school Arts et Metiers

ParisTech and validated in the present study in a population of adolescents with scoliosis. This new method is simpler and more accurate than the use of a plumb line to estimate coronal trunk balance either clinically or radiographically.

Our findings about the reliability of gravity line localisation using biplanar radiographs in patients with scoliosis are consistent with those obtained by Amabile et al. in healthy individuals [8] (Table 1). Gravity line localisation seems more accurate in the coronal than the sagittal plane, probably due to arm position during image acquisition and to the body contour reconstruction method, which cannot take arm position into account.

Plumb line and gravity line criteria for trunk imbalance correlated significantly with each other. Nevertheless, in many patients, disagreement was found between the results of the two methods.

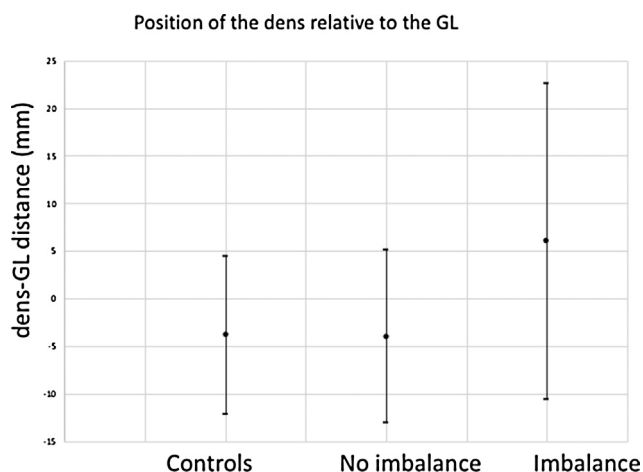


Fig. 6. Mean \pm SD distance between the dens and the gravity line. GL: gravity line.

Thus, 21% of patients without imbalance by plumb line localisation had an imbalance by gravity line localisation (plumb line false-negative results). On the other hand, 55% of patients without imbalance by gravity line localisation had an imbalance by plumb line localisation patients (gravity line false-negative results). In the first case, gravity line assessment may increase the number of patients selected for surgery. In the second, a substantial number of patients in whom surgery is considered based on the plumb line assessment may be deemed not to require surgery.

The T1V/S distance cut-offs that indicated coronal trunk imbalance were $+17.8$ mm and -18.7 mm. These values make clinical sense and are similar to those found in earlier studies (10 mm in Ramirez et al. [15] and 20 mm in Souder et al. [2]). No consensus exists at present about these cut-off values, and we therefore determined the normal range in a population of healthy adolescents. Le Huec et al. [16] described the gravity line as running through the midpoint of the line connecting the two femoral heads in the coronal plane. We therefore used GL/HA to evaluate gravity line position in our populations of patients with scoliosis. The mean GL/HA distance in our healthy controls was -0.46 ± 9.1 mm, which would seem to support our approach.

Gauchard et al. [17] reported that imbalance was the rule in patients with thoracic or thoraco-lumbar scoliosis, in contradiction to others, such as Fortin et al. [3]. Our results agree with those reported by Gauchard et al. [17], with significantly greater GL/HA distances in the subgroups with thoracic or thoraco-lumbar scoliosis. However, the small size of the subgroups in our study warrant caution in interpreting our findings and support the need for further evaluations in larger populations.

Several studies have investigated the usefulness of including head position in assessments of postural alignment [16,18]. The distance between the dens and the gravity line seems to vary little in healthy individuals (SD = 8 mm). We found no difference between the controls and the patients without coronal trunk imbalance. Among the patients with imbalance, 40% successfully compensated for the shift in T1 position, maintaining the position of the head relative to the gravity line within the normal range. The remaining 60% whose head position was abnormal may constitute a smaller subgroup of patients with true imbalance requiring particular caution. Nevertheless, 90% of patients with imbalance were able to keep their head above the pelvis, i.e., to maintain the coronal-plane dens-HA angle within the normal range. This angle is stable in healthy and in ageing individuals [18]. Our results suggest that it may also remain stable in patients who have scoliosis with or without imbalance. In other words, even when T1 is displaced, a compensatory mechanism at the cervical spine ensures that the

head remains above the pelvis, as reported by Amabile et al. [8,18]. In some cases, however, this compensatory mechanism changes the position of the dens and femoral head centres relative to the gravity line. The change in dens position may be the most obvious and discriminatory sign.

The assessment of posture using biplanar radiography involves specific constraints and requires faultless image acquisition. Several of the patients initially recruited to our study were excluded due to inappropriate position during image acquisition [12]. The impact of incorrect free-standing position remains to be determined but may include alterations in overall trunk balance.

Our study consisted of a 2D evaluation in the coronal plane of a 3D deformity. This fact limited the risk of bias, since the coronal plane is determined relative to the patient and not to the imaging plane, so that bias due to faulty patient position relative to the imaging plane is eliminated. Studies are ongoing to evaluate the same parameters in the sagittal and axial planes with the goal of gaining new understanding into overall trunk balance alterations in patients with idiopathic scoliosis.

5. Conclusion

For the assessment of coronal trunk balance, plumb line position is roughly equivalent to gravity line localisation using biplanar radiographs. The plumb line method is less accurate, however, and may either overestimate or underestimate postural imbalance. Therefore, the plumb line method should not be used alone to affect surgical decisions. Gravity line localisation to evaluate overall trunk balance holds promise for monitoring patients with spinal deformities. This method provides both diagnostic and prognostic information and provides a new objective criterion for assessing 3D spinal alignment.

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Authors' contributions

T. Hernandez: Technique study validation, model developing, performed the statistical analysis and drafted the article.

T. Thénard: programmed the modelling software.

C. Vergari: performed the statistical analysis, drafted the article, and oversaw the project.

L. Robichon: programmed the software and validated the study technique.

W. Skalli: original idea, global project managing.

R. Vialle: original idea, global project managing.

Disclosure of interest

The authors declare that they have no competing interest.

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