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Correlations linking static quantitative gait analysis parameters to radiographic parameters in adolescent idiopathic scoliosis

Sébastien Pesenti[a,b,c,*], Solène Prost[a,b], Benjamin Blondel[a,b,c], Vincent Pomero[b], Mathieu Severyns[a], Lionel Rosciglni[a,b], Guillaume Authier[b], Elke Viehweger[a,b,c], Jean-Luc Jouve[a,b,c]

[a] Service d'orthopédie pédiatrique, Aix-Marseille université, Timone Enfants, Marseille, France
[b] Plateforme d'analyse de la motricité, Aix-Marseille université, Timone, Marseille, France
[c] Orthopédie pédiatrique, CNRS, ISM, Aix-Marseille université, hôpital de la Timone, AP–HM, Marseille, France

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ABSTRACT

Background: Radiography is the main tool used to assess spinal deformities in patients with adolescent idiopathic scoliosis (AIS) but requires repeated exposure to ionising radiation, potentially raising safety concerns. Consequently, new methods are needed. Among them, the acquisition of static parameters during quantitative gait analysis (QGA) has received attention in recent years. However, no data on correlations linking static QGA parameters to standard radiographic parameters are available. The objective of this study was to assess correlations between static QGA parameters and standard radiographic parameters in patients with AIS.
Hypothesis: Spinal deformities in patients with AIS can be evaluated based on static QGA parameters.
Patients and methods: We studied patients scheduled for surgery to treat AIS. On the day before surgery, QGA was performed and antero-posterior and lateral radiographs obtained. QGA involved analysing the positions of 32 reflective markers, including 6 used to assess the spine. The coronal vertical axis (CVA), thoracic and lumbar Cobb angles, sagittal vertical axis (SVA), thoracic kyphosis, lumbar lordosis, and pelvic tilt were recorded and compared to the corresponding radiographic parameters.
Results: The study included 57 patients, including 48 (84%) females, with a mean age of 15.2 years. Among them, 45 had Lenke 1 and 12 Lenke 5 scoliosis. The mean main Cobb angle was 51.9°. In the coronal plane, significant correlations with the corresponding radiographic parameters were found for the CVA ($R = 0.524$, $p < 0.01$) and thoracic Cobb angle ($R = 0.599$, $p < 0.01$). All the sagittal parameters correlated significantly with the corresponding radiographic parameters: SVA, $R = 0.313$; pelvic tilt, $R = 0.342$; thoracic kyphosis, $R = 0.575$; and lumbar lordosis, $R = 0.360$ ($p < 0.05$ for all four parameters).
Conclusions: In this study, static QGA parameters accurately reflected the spinal deformities visualised radiographically. The lumbar deformity was more difficult to characterise, probably because it was mild in our population. Research efforts should focus on improving the performance of QGA, notably for detecting curve progression. Thus, QGA may allow a decrease in radiation exposure of patients with AIS.
Level of evidence: III.

1. Introduction

Adolescent idiopathic scoliosis (AIS) is a three-dimensional spinal deformity seen in 2% to 4% of adolescents [1]. Rotation of the vertebra at the apex of the spinal curve results in a characteristic deformity in the coronal plane and may alter the sagittal curvatures. Physical examination of the gibbus and plumb line measurements provide some information on the deformities. To obtain more accurate data, radiographs must be obtained and used to measure the Cobb angles of the various coronal curves, thoracic kyphosis and lumbar lordosis in the sagittal plane, and several pelvic parameters.

A quantitative evaluation of the deformities based on radiographic parameters is crucial not only to establish the diagnosis, but also to monitor the deformities throughout adolescence and to guide treatment decisions. As a rule, radiographs must be obtained every 6 to 12 months during the growth period. However, the resulting repeated exposure to ionising radiation is associated with

* Corresponding author at: Service d'orthopédie pédiatrique, hôpital d'enfants de la Timone, 264, rue Saint-Pierre, 13005 Marseille, France.
E-mail address: seb.pesenti@gmail.com (S. Pesenti).

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increased risks of infertility and of breast and endometrial cancer [2–4]. Although the recent introduction of low-dose biplanar radiography has significantly decreased radiation exposure, the effects of repeatedly receiving even low doses of X-rays are unclear. Consequently, non-irradiating methods for evaluating and monitoring AIS are needed. Another disadvantage of radiography is that the images are obtained in a constrained position and environment. The position in which the radiographs are obtained may not reflect the position adopted by the patient during everyday activities, thus introducing bias into the postural analysis.

Quantitative gait analysis (QGA) was initially developed as a tool for evaluating lower limb kinematics [5,6]. Reflective markers are placed at various sites on the skin and their movements are captured to describe the positions adopted by each limb segment in space. QGA was first extensively used in patients with orthopaedic abnormalities related to neurological conditions. It is now being developed for other fields such as lower-limb joint replacement surgery [7]. An increasing number of QGA protocols for evaluating the spine have been described. However, these protocols are cumbersome, lack efficiency, and are difficult to apply to clinical practice as they require a large number of markers to describe the spine [8]. In 2012, Blondel et al. reported a simplified protocol for obtaining an accurate kinematic analysis of the spine [9]. However, no data on correlations linking QGA parameters obtained using this protocol to the standard radiographic parameters are available.

The objective of this study was to assess correlations between static QGA parameters and standard radiographic parameters in patients with AIS. Our working hypothesis was that spinal deformities in patients with AIS could be evaluated based on static QGA parameters.

2. Patients and methods

2.1. Study population

A single-centre prospective study was performed after being approved by our institutional review board. From January 2014 to December 2017, consecutive patients scheduled for surgery to treat AIS at our institution were included. The patients had either a single curve with a thoracic Cobb angle greater than 45° (Lenke 1) or a thoracic or thoraco-lumbar curve with a Cobb angle greater than 35° (Lenke 5). Exclusion criteria were a history of major trauma or orthopaedic disorders of the lower limbs or spine, previous spinal surgery, and transitional vertebrae.

2.2. Study protocol

Low-dose biplanar antero-posterior and lateral radiographs of the spine (EOS Imaging, Paris, France) were obtained on the day before surgery. QGA was then performed. Marker motion capture was with an optoelectronic system (Vicon, Oxford, UK) with six high-resolution infrared cameras and a 100-Hz sampling frequency. Each patient was equipped with 36 reflective markers placed on the skin at the sites described by Blondel et al. Among these markers, 6 were placed on the spinous processes of C7, T6, T9, T12, L3, and S1 and served to describe the spine (Fig. 1). The marker on S1 and the markers on each of the two antero-superior iliac spines provided information on the position of the pelvis. Static parameters were acquired with the patients standing immobile, in a comfortable position, with the arms along the sides, for 10 seconds. The same position was used in all the patients.

2.3. Data collection

Height and weight were collected and the body mass index (BMI) computed. All radiographic parameters were measured by

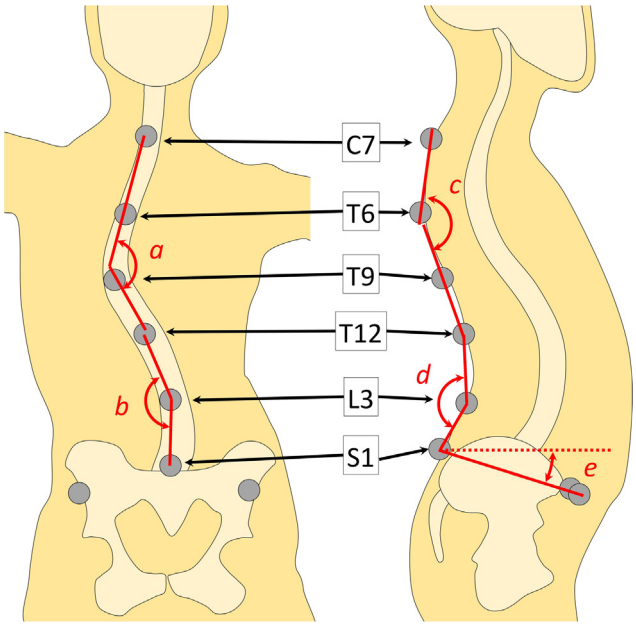

Fig. 1. Protocol for positioning the reflective markers and measuring the static quantitative gait analysis parameters. The six markers placed on the spine were on the spinous processes of C7, T6, T9, T12, L3, and S1. The following parameters were measured: a: thoracic angle in the coronal plane; b: lumbar angle in the coronal plane; c: thoracic angle in the sagittal plane; d: lumbar angle in the sagittal plane: e: pelvic tilt.

the same observer (SP) using dedicated spinal radiograph analysis software (Surgimap, New York, NY, USA). The antero-posterior radiograph was used to measure the thoracic and lumbar Cobb angles and the coronal vertical axis (CVA). Rotation of the vertebra at the apex of the curve was measured using the Raimondi template. The lateral radiograph served to measure thoracic kyphosis between T4 and T12, lumbar lordosis between L1 and S1, pelvic tilt, and the sagittal vertical axis (SVA).

The following QGA parameters were recorded: in the coronal plane, the thoracic and lumbar angles and the CVA; and in the sagittal plane, the thoracic and lumbar angles, pelvic tilt, and the SVA (Fig. 1). The thoracic angle in the coronal and sagittal planes was the angle subtended by the line through the centres of the C7 and T6 markers and the line through the centres of the T9 and T12 markers. The lumbar angle in the coronal and sagittal planes was formed by the line through the centres of the T12 and L3 markers and the line through the centres of the L3 and S1 markers. Pelvic tilt was the angle between the horizontal and the line through the S1 marker and the markers on the antero-superior iliac spines. Finally, the CVA and SVA were the horizontal distances between the S1 markers and the vertical line through the centre of the C7 marker, in the coronal and sagittal planes, respectively. The reconstructions were performed by two observers (VP et GA) (Fig. 2).

2.4. Statistical analysis

The study variables were described as mean, median, and range. Pearson's correlation coefficients were computed between each radiographic parameter and the corresponding QGA parameter, as follows: thoracic Cobb angle and thoracic QGA angle in the coronal plane; lumbar Cobb angle and lumbar QGA angle in the coronal plane; X-ray CVA and QGA CVA; thoracic kyphosis and QGA thoracic angle in the sagittal plane; lumbar lordosis and QGA lumbar angle in the sagittal plane; X-ray pelvic tilt and QGA pelvic tilt; and X-ray SVA and QGA SVA. Then, forced linear regression was performed to assess associations between radiographic and QGA

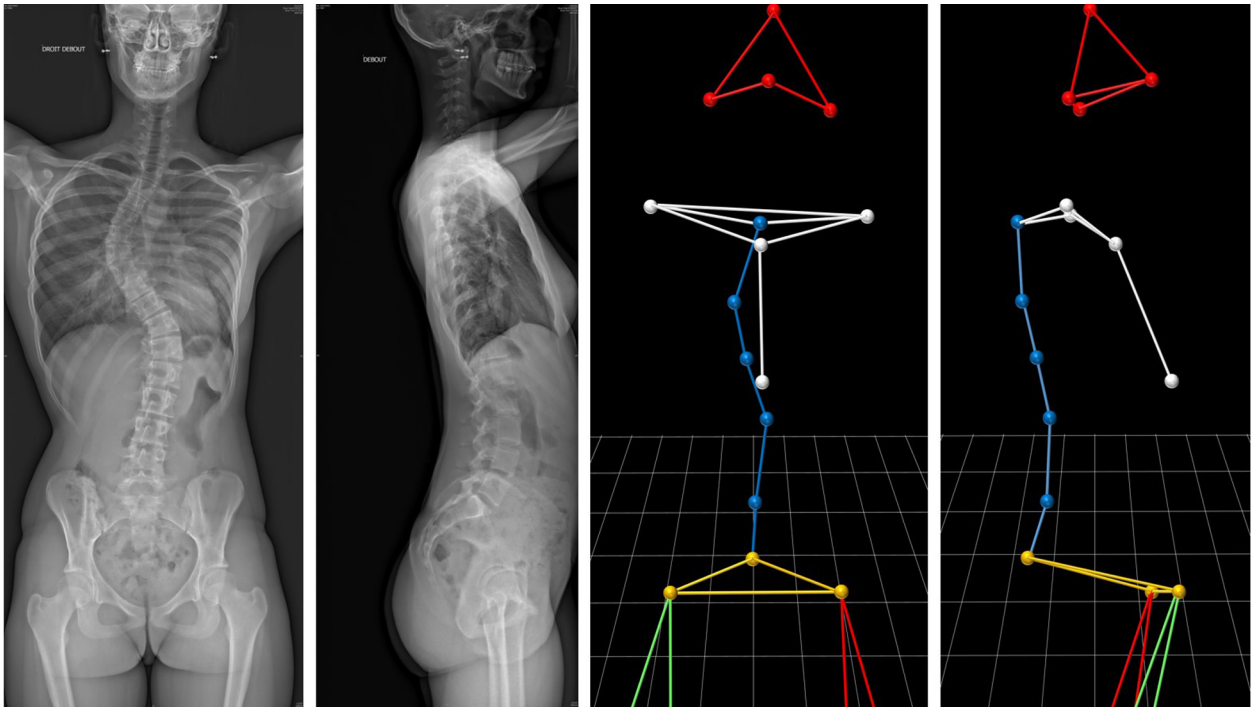

Fig. 2. Female with Lenke 1 scoliosis: standard radiographs on the left and quantitative gait analysis-based reconstruction in the coronal and sagittal planes on the right.

Table 1
Clinical and radiographic parameters in the 57 study patients.

	Mean	Range	Median
Age (years)	15.2	12–21	15.2
Weight (kg)	48	35–80	48
Height (cm)	160	145–177	160
Body mass index (kg/m^2)	19.2	14.7–31	19.2
Main Cobb angle (°)	51.9	35–76	54
Thoracic Cobb angle (°)	47.8	12–76	49
Lumbar Cobb angle (°)	36.8	17–65	36
CVA (mm)	15.4	0–44	13
Raimondi angle (°)	24	12–40	24
Thoracic kyphosis (T4-T12) (°)	20.3	−2–59	22
Lumbar lordosis (L1-S1) (°)	51.1	13–74	51
Pelvic tilt (°)	6.6	−9–25	7
SVA (mm)	21.6	1–87	18

CVA: coronal vertical axis; SVA: sagittal vertical axis.

parameters. Analyses were performed in subgroups defined by the median values of BMI, the Raimondi angle, the Cobb angle, the thoracic kyphosis angle, and the lumbar lordosis angle. Values of p lower than 0.05 were taken to indicate significant differences.

3. Results

3.1. Study population

We included 57 patients, 48 females and 9 males with a mean age of 15.2 years (range, 12–21 years). The major curve was right thoracic (Lenke 1) in 45 patients and left thoraco-lumbar and lumbar (Lenke 5) in 12 patients. The main mean Cobb angle in the overall population was 51.9°. Table 1 reports the main clinical and radiographic parameters.

3.2. Correlations between radiographic and quantitative gait analysis (QGA) parameters

Table 2 reports the results of the correlation analyses. In the coronal plane, all radiographic and QGA parameters within each pair were significantly correlated, except the lumbar Cobb angle and lumbar QGA angle. The strongest correlation was between the thoracic Cobb angle and thoracic QGA angle ($R = 0.599$; $p < 0.001$). In the sagittal plane, all parameters within each pair showed significant correlations (all p-values < 0.05). Table 3 shows the results of the linear regression analysis.

3.3. Subgroup analyses

Stratifying the patients based on the median values of the radiographic parameters produced the following results. No significant correlations between the radiographic parameter and corresponding QGA parameter were found in the subgroups with below-median values of the main Cobb angle (median, 54°; $R = 0.329$; $p = 0.09$), lumbar Cobb angle (median, 36°; $R = -0.124$; $p = 0.95$), and thoracic kyphosis ($R = 0.309$, $p = 0.09$). In the subgroups with radiographic parameter values equal to or above the median, all QGA parameters except the lumbar Cobb angle correlated significantly with the corresponding radiographic parameters. Tables 2 and 4 report the results of the subgroup analyses.

4. Discussion

This study is among the first to address potential correlations linking standard radiographic parameters to QGA parameters in a population of patients with scoliosis. The findings confirm our working hypothesis: QGA is effective in describing the spinal deformities seen in AIS. We found that QGA parameters reflected standard radiographic parameters used to assess scoliosis. In a 2012 assessment in healthy volunteers of the QGA protocol used in our study, accurate kinematic data were obtained using only a limited number of markers [9].

Most published studies of the QGA evaluation of AIS relied solely on parameters collected at the lower limbs and shoulders and on overall spinal balance [10–13]. The spine was usually handled as a unit, as opposed to being divided into several segments. A 2012

Table 2
Correlations between radiographic and quantitative gait analysis parameters in the overall population and in subgroups defined based on median values.

Category	Parameter	Overall population		Group < Median		Group ≥ Median	
		Correlation	*p*-value	Correlation	*p*-value	Correlation	*p*-value
X-ray	Main Cobb angle	0.499	< 0.001	0.329	0.09	0.495	0.007
QGA	Main thoracic angle						
X-ray	Thoracic Cobb angle	0.599	< 0.001	0.528	0.005	0.531	0.002
QGA	Coronal thoracic angle						
X-ray	Lumbar Cobb angle	−0.09	0.501	−0.124	0.95	0.01	0.62
QGA	Coronal lumbar angle						
X-ray	Coronal Vertical Axis	0.524	< 0.001	–	–	–	–
QGA	Coronal Vertical Axis						
X-ray	Thoracic kyphosis, T4-T12	0.575	< 0.001	0.309	0.09	0.685	<0.001
QGA	Sagittal thoracic angle						
X-ray	Lumbar lordosis, L1-S1	0.36	0.007	0.424	0.03	0.361	0.05
QGA	Sagittal lumbar angle						
X-ray	Pelvic tilt	0.342	0.009	–	–	–	–
QGA	Pelvic tilt						
X-ray	Sagittal vertical axis	0.313	0.002	–	–	–	–
QGA	Sagittal vertical axis						

QGA: quantitative gait analysis.

Table 3
Values of quantitative gait analysis parameters and results of the linear regression analysis.

	Mean	Range	Linear regression
Main coronal angle	14.0	0–32	ParX-ray = 2.9 × ParQGA
Coronal thoracic angle	13.1	0–32	ParX-ray = 2.9 × ParQGA
Coronal lumbar angle	10.7	0–28	–
Coronal Vertical Axis	16.1	0–53	ParX-ray = 0.77 × ParQGA
Sagittal thoracic angle	27.1	10–60	ParX-ray = 0.75 × ParQGA
Sagittal lumbar angle	22.5	5–48	ParX-ray = 2.11 × ParQGA
Pelvic tilt	12.1	−4–23	ParX-ray = 0.33 × ParQGA
Sagittal Vertical Axis	28.9	3–68	ParX-ray = 0.48 × ParQGA

Par-X-ray: radiographic parameters; Par-QGA: quantitative gait analysis parameters.

report by Ranavolo et al. compared several QGA protocols in 10 healthy volunteers [8]. The objective was to identify the best set of markers (7 to 15) for reflecting the radiographic thoracic kyphosis and lumbar lordosis. Placing 9 to 10 markers on the spine estimated the sagittal spinal curves with 5° of accuracy. The most often used marker sites were C7, T5, T8, L1, L3, and L5. However, protocols that require a large number of markers are not suitable for use in clinical practice. We used only 6 markers (C7, T6, T9, T12, L3, and S1). Although using a smaller number of markers decreases the accuracy of curve measurements, the QGA results nevertheless reflected the standard radiographic parameters. The use of only 6 markers may be feasible in clinical practice.

The results of the subgroup analyses suggest that QGA may perform better in describing severe compared to mild deformities. In the subgroup with below-median radiographic parameter values, most of the static QGA parameters failed to correlate significantly with the corresponding radiographic parameters.

In our study, QGA was highly effective in describing the thoracic spine, in both the coronal and the sagittal planes. Accuracy was far lower in describing the lumbar spine. One possible explanation to this difference is the thinner subcutaneous tissue at the thoracic compared to the lumbar level, which results in the thoracic reflective markers being located closer to the bony landmarks and therefore probably providing a more accurate description of the shape of the spine. In addition, the larger number of markers at the thoracic spine ($n = 4$) compared to the lumbar spine ($n = 3$) probably resulted in greater accuracy. Finally, the lumbar spine has a greater range of motion compared to the thoracic spine and contributes considerably to posture regulation. Thus, the overall position of the patient influences the shape of the lumbar spine, notably in the sagittal plane [14,15]. A reasonable hypothesis is that the position of the patient during static QGA parameter acquisition differs somewhat from the position during radiograph acquisition and that this difference translates into some measure of discrepancy between lumbar radiographic and QGA parameters. Further investigations to assess this possibility are needed.

In addition to providing an evaluation of overall spinal shape, QGA emerged in our study as a potentially useful tool for describ-

Table 4
Correlations in subgroups defined based on the median values of the body mass index and Raimondi's angle.

Category	Parameter	Overall population		BMI < 19.2		BMI ≥ 19.2		Raimondi angle < 24°		Raimondi angle > 24°	
		Correlation	*p*-value	Correlation	*p*-value	Correlation	*p*-value	Correlation	*p*-value	Correlation	*p*-value
X-ray	Main Cobb angle	0.499	< 0.001	0.528	0.02	0.469	0.04	0.401	0.03	0.513	> 0.01
QGA	Main thoracic angle										
X-ray	Thoracic Cobb angle	0.599	< 0.001	0.511	0.03	0.666	0.002	0.539	< 0.01	0.619	> 0.01
QGA	Coronal thoracic angle										
X-ray	Lumbar Cobb angle	−0.09	0.501	−0.266	0.29	0.197	0.43	−0.119	0.54	−0.099	0.60
QGA	Coronal lumbar angle										
X-ray	Coronal Vertical Axis	0.524	< 0.001	0.462	0.05	0.537	0.02	–	–	–	–
QGA	Coronal Vertical Axis										
X-ray	Thoracic kyphosis, T4-T12	0.575	< 0.001	0.619	< 0.01	0.260	0.29	0.486	< 0.01	0.538	< 0.01
QGA	Sagittal thoracic angle										
X-ray	Lumbar lordosis, L1-S1	0.36	0.007	0.540	0.02	0.325	0.19	0.445	0.01	0.314	0.10
QGA	Sagittal lumbar angle										
X-ray	Pelvic tilt	0.342	0.009	0.635	< 0.01	0.178	0.48	–	–	–	–
QGA	Pelvic tilt										
X-ray	Sagittal Vertical Axis	0.313	0.002	0.824	< 0.01	-0.03	0.90	–	–	–	–
QGA	Sagittal Vertical Axis										

BMI: body mass index; QGA: quantitative gait analysis.

ing overall spinal balance. By QGA, balance in the coronal (CVA) and sagittal (SVA) planes correlated closely with the corresponding radiographic parameters ($R = 0.524$, $p < 0.001$ and $R = 0.313$, $p = 0.002$, respectively). As these parameters are related solely to position, they are easier to retrieve by QGA compared to anatomical parameters such as Cobb angles and sagittal curvatures. Consequently, QGA may prove extremely useful for evaluating overall spinal alignment in patients with spinal deformities. Studies have established that sagittal malalignment is the parameter most closely correlated to impaired quality of life in adults [16,17]. Sagittal malalignment is probably underestimated on radiographs taken in a constrained position. QGA may more accurately reflect sagittal malalignment. At present, the Cobb angle value is virtually the only parameter used to make surgical decisions in patients with scoliosis. Studies involving pre- and postoperative dynamic investigations combined with quality-of-life assessments may allow the identification of other parameters relevant to deformity evaluation, such as overall spinal alignment.

QGA has several limitations. Our subgroup analysis showed that an above-median BMI was associated with decreased accuracy of the evaluation of most parameters (lumbar Cobb angle, thoracic kyphosis, lumbar lordosis, pelvic tilt, and SVA). The reason is probably greater difficulty in locating the bony landmarks in patients with a thick layer of subcutaneous fat. Nevertheless, AIS is associated with a characteristic habitus that includes a low BMI. Clearly, limitations to QGA arise due to difficulties in reconstructing the shape of the spine based only on identification of the spinous processes. Nonetheless, it should be noted that the small sample sizes in the subgroup analyses may have limited our ability to detect statistically significant associations.

The amount of vertebral rotation did not affect the QGA measurements. Although most QGA parameters correlated significantly with their corresponding radiographic parameters, all correlation coefficients were smaller than 0.650, probably due to variability in marker position. Importantly, QGA is not intended as a substitute for the radiographic analysis. We believe that QGA could be used to monitor the curves provided new radiographs are obtained if the results suggest curve progression.

Research efforts should focus on evaluating mild deformities. Our study demonstrated that overall spinal shape can be evaluated by QGA using a limited number of markers. Now, QGA needs to be evaluated as a tool for monitoring patients who are not treated surgically. It would be useful to know whether QGA is effective in detecting curve progression between two follow-up visits. If it is, the radiographic assessments could be obtained at wider intervals. In addition, dynamic parameters, notably those obtained during walking, may provide an overall evaluation of spinal function. The present study established that static QGA parameters reflected standard radiographic parameters. A study of changes in dynamic QGA parameters would be of interest.

5. Conclusion

Our findings demonstrate that QGA parameters describe the deformities related to AIS, as well as overall spinal alignment. However, at the lumbar spine, the small number of markers translates into limited accuracy. QGA is an effective tool whose continuing development may decrease the radiographic needs of patients with AIS, thereby limiting their exposure to ionising radiation. Future research should strive to effectively describe each of the spinal segments. Furthermore, the limited portability of the measurement systems virtually restricts the use of QGA to clinical research.

The use of QGA for a dynamic analysis of the spine may identify new objective parameters reflecting spinal function in patients with spinal deformities.

Disclosure of interest

The authors declare that they have no competing interest.

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Contributions of each author

All authors contributed equally to the manuscript and approved its final version.

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