Influence of patient rotational malpositioning on pelvic parameters assessed on lateral radiographs

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AIM: To estimate the effect of patients' axial rotation (AR) during pelvic radiograph acquisition, on the reliability and validity of sagittal pelvic parameters.

MATERIALS AND METHODS: Lateral digitally reconstructed radiographs (LDRRs) were obtained from the pelvic computed tomography (CT) scans of eight children and nine adults. Then, the AR of the pelvis was simulated and the corresponding LDRRs were reconstructed at 5°, 10°, 15°, and 20° of the AR. Pelvic parameters were measured digitally on each radiograph. Intra- and interobserver variability were evaluated at each AR position (three operators repeated the measurements three times each). The bias on each clinical parameter, in each AR position, was calculated relatively to the 0° position.

RESULTS: Interobserver variability increased similarly in children and adults with AR. It reached 4.4° for pelvic incidence and 4.7° for the sacral slope at 20° of AR. Biases on radiological parameters increased with AR and exceeded the acceptable threshold of errors when AR reached 10°. A linear regression was established (R^2=0.834, $p<0.0001$) in order to estimate the AR of a patient on a lateral pelvic radiograph based on the measurement of the bifemoral distance normalized to the sagittal pelvic thickness.

CONCLUSIONS: AR of patients during radiograph acquisition can be estimated in clinical practice, which would allow physicians to discard any radiographs where the calculated AR exceeded 10°.

Introduction

The sagittal curvatures of the spine vary greatly among asymptomatic subjects,[1] and it has been widely demonstrated that sagittal spine curvatures are highly correlated to pelvis morphological and positional parameters.[2–4] Pelvic incidence was proposed as an anatomical parameter[5] that quantifies the relative inclination of the sacrum within the iliac bones and correlates with the sagittal curvatures of the spine.[6] A classification of the normal morphotypes of the sagittal pelvis and spine, mainly based on the sacral slope,[3] ensued in order to guide sagittal correction of spinal curvatures.[7] Thus, for preoperative planning, the desired postoperative sagittal curvatures should be based on the morphology of the pelvis, quantified by pelvic incidence and sagittal pelvic thickness,[8] as well as on other important positional parameters of the pelvis, namely sacral slope, pelvic tilt,[6] and pelvic inclination.[9] These parameters are of paramount importance in the radiographic evaluation of a large range of spinal pathologies such as spondylolisthesis, adolescent idiopathic scoliosis, adult spinal deformity, but also degenerative conditions.[10,11]

Although these parameters are easily accessible on standard full-spine sagittal radiographs, their measurements can be biased by a number of factors including the two-dimensional (2D) nature of the radiograph, as it projects three-dimensional structures onto a bi-dimensional plane, and the potential malpositioning of patients during radiograph acquisition. Therefore, it is crucial to quantify the errors associated with this technique, especially those related to patient malpositioning during radiograph acquisition. Although tilting the pelvis in the sagittal plane would affect the positional parameters, it would not affect the anatomical parameters; however, axial rotation of the pelvis in the horizontal plane could influence the lateral projection of the pelvis, and thus, all of the measured parameters. Moreover, it would be useful for physicians to have a tool to easily estimate the axial rotation of patients during radiograph acquisition solely from the available lateral pelvic radiograph.

The primary aim of the present study was to evaluate the effect of axial malpositioning of the patient during lateral pelvic radiograph acquisition on both the validity and reliability of commonly measured pelvic parameters. The secondary aim of this study was to provide a simple equation to estimate patient axial rotation in order to decide on the eligibility of lateral radiographs.

Materials and methods

Sample

Helical pelvic computed tomography (CT) scans of nine adults and eight children (0.6 mm slice thickness, 512×512 resolution, 0.768 mm pixel spacing) were extracted from the database of the radiology department of University of Saint-Joseph, Beirut, Lebanon. All patients had undergone CT in order to investigate visceral pain. Adult patients (four male, five female) had an average age 55.6 (standard deviation [SD] 24.5) years, ranging from 22–80 years. Paediatric patients (five male, three female) had an average age 12 (SD 2.2) years, ranging from 9–15 years. All patients who undergo tests at the university hospital systematically sign authorization for the use of their anonymous data for research purposes. The design of the present study had been approved by the institutional review board of the institution.

Lateral digitally reconstructed radiographs (DRRs) were simulated from each CT dataset in a DICOM (digital imaging and communications in medicine) format, with squared pixels (pixel spacing = 0.141mm), using specific software developed at Arts et Métiers ParisTech (Paris, France). This technique had been previously used[12–14] and allows the simulation of the axial rotation of X-ray beams in any direction: (1) the generation of a lateral DRR is based on linear scanning by the X-ray beams from the top to the bottom of the CT volume with cylindrical projections: a collimator is simulated to avoid vertical divergence of the X-rays and to allow only horizontal propagation. The horizontal enlargement was corrected by applying a scaling factor on the image, in order to measure exact lengths on the radiographs. (2) Pelvic rotation was mimicked by rotating the CT volume around the vertical axis. Thus, five DRRs were generated from each CT examination, while introducing an axial rotation from 0° to 20° with 5° increments (Fig 1).

Radiological parameters

Radiological parameters were measured digitally on each radiograph using the SterEOS 2D toolbox (version 1.5.1; EOS-Imaging, Paris, France). The following parameters were measured (Fig 2): sagittal pelvic thickness (mm), pelvic incidence (degrees), pelvic tilt (degrees), sacral slope (degrees),[8] pelvic inclination (degrees),[9] and the bi-femoral distance (mm), which was defined as the length of the horizontal line drawn between the centres of the two femoral heads.

Data processing

Three orthopaedic residents were recruited from the university hospital and were repeatedly trained on the methods of measurement. The six parameters were measured on each DRR, in each pelvic axial rotation position (0°, 5°, 10°, 15°, 20°) three times by each of the three independent trained operators. Repeated measurements were separated by 2-week intervals. Nine values were thus obtained for each parameter, at each axial rotation position. The values measured at 0° of axial rotation were considered as the reference. The reproducibility (SR) SD, which includes both intra- and interobserver variability, was calculated for each parameter, at each axial rotation position, according to the guidelines of the ISO 5725-2 standard.[15] The variability was assessed in both children and adults. Moreover, the intraclass correlation coefficient (ICC), (2,k) model, was calculated in order to evaluate the intra- and interobserver agreement for each parameter: ICC>0.80 indicates very high reliability, 0.60–0.79 moderately high reliability, 0.40–0.59 moderate reliability, and <0.40 low reliability.[16]

Furthermore, in order to evaluate the bias at each axial rotation increment, the mean value of the nine measurements (three operators, three measurements each) of each parameter was compared to the mean value measured at 0° position. The threshold value for the acceptable bias was set as the uncertainty of measurement at 0°, defined as the

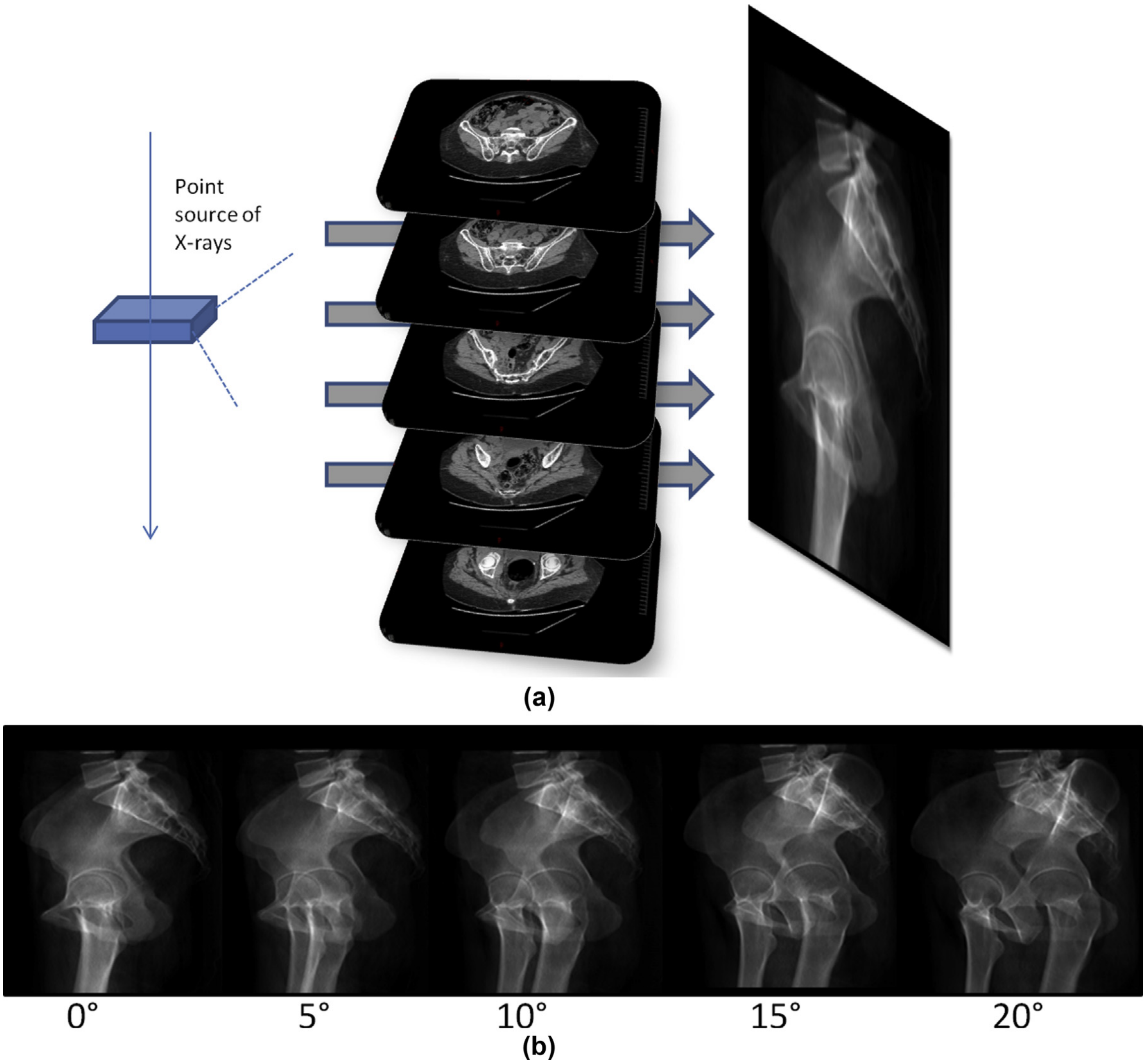

Figure 1 Generation of lateral DRR from CT images (a) with an example of lateral DRRs at different axial rotation positions (b).

95% confidence interval (95% CI=2SR). The number of patients whose biases exceeded these thresholds was reported.

Moreover, the statistical differences in bias between children and adults were investigated using Student's *t* or Mann–Whitney tests depending on the distribution (Shapiro–Wilk test for normality).

In order to estimate the axial rotation from the lateral X-ray, a linear regression was computed between axial rotation position and bifemoral distance normalized to sagittal pelvic thickness. The level of significance for all previously described tests was set at $p<0.05$. Calculations and statistics were performed using MATLAB (Mathworks, Natick, MA, USA) and Xlstat (Addinsoft, Paris, France).

Results

Reproducibility of radiographic parameters

The reproducibility (SR) of the radiographic parameters, at each axial rotation position, in both children and adult groups are displayed in Fig 3. In the adult group and in the absence of axial rotation (i.e. AR=0°), the reproducibility was 2.5° for pelvic incidence and sacral slope, 0.8° for pelvic inclination and 0.7° for pelvic tilt. For an axial rotation of 20°, the reproducibility increased to 4.4° for pelvic incidence, 4.7° for sacral slope, 3.4° for pelvic inclination and 2.0° for pelvic tilt. The results for pelvic thickness and bifemoral distance were not reported on the same graph with the parameters cited above for reasons of legibility. High reproducibility was found (SR = 0.20 mm) for both parameters, in both children and adults and were constant for all axial rotation positions. The intra- and interobserver ICC values were >0.8 for all parameters in all axial rotation positions, ranging between 0.82 and 0.98, indicating very high intra- and interobserver agreement.

Bias to the reference

The average absolute biases of the calculated parameters, at each axial rotation position, relatively to the value of the parameter measured in the absence of axial rotation, are reported in Fig 4 for sacral slope, pelvic tilt, pelvic incidence,

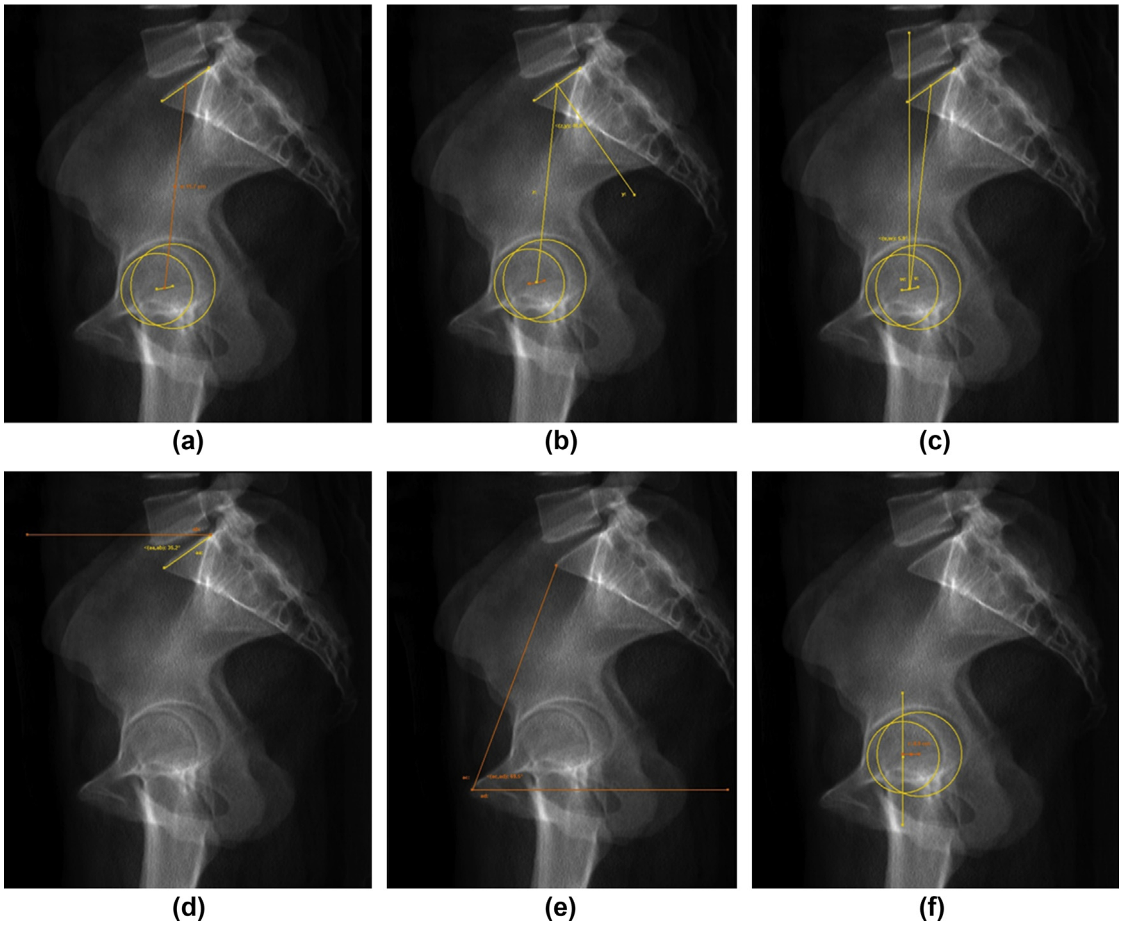

Figure 2 Representation of the measured pelvic parameters on lateral radiographs using the SterEOS 2D toolbox: (a) sagittal pelvic thickness, (b) pelvic incidence, (c) pelvic tilt, (d) sacral slope, (e) pelvic inclination, (f) bifemoral distance.

and pelvic inclination. The number of subjects that exceeded the threshold of 2SR at 0° of axial rotation is noted above each bar. The biases increased with the degree of axial rotation for all radiological parameters. The average biases and their standard deviations were consistently lower in adults compared to the children's group; however, the biases were not significantly different between the two groups ($p>0.05$).

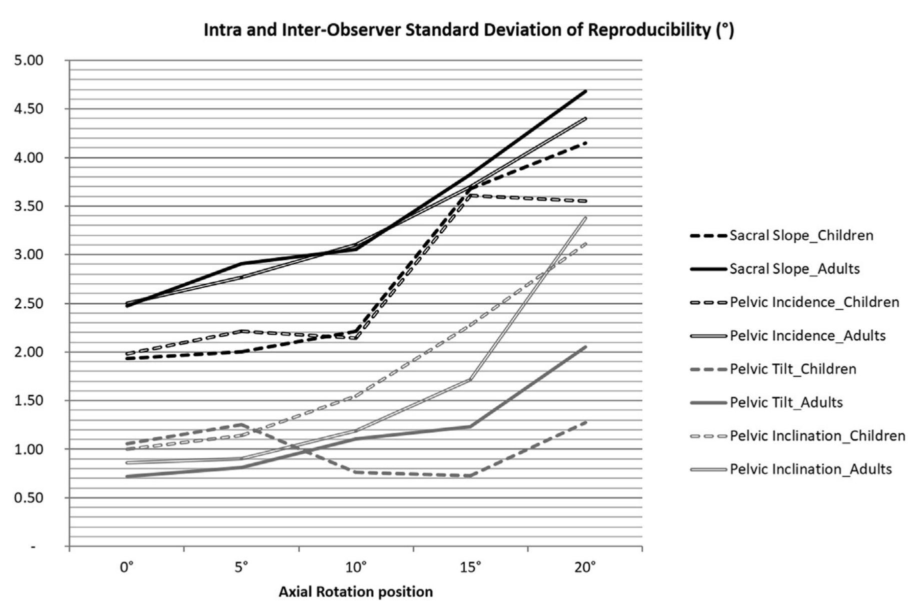

Figure 3 Intra and interobserver (SR) reproducibility for pelvic parameters at all axial rotation positions in both children and adult groups.

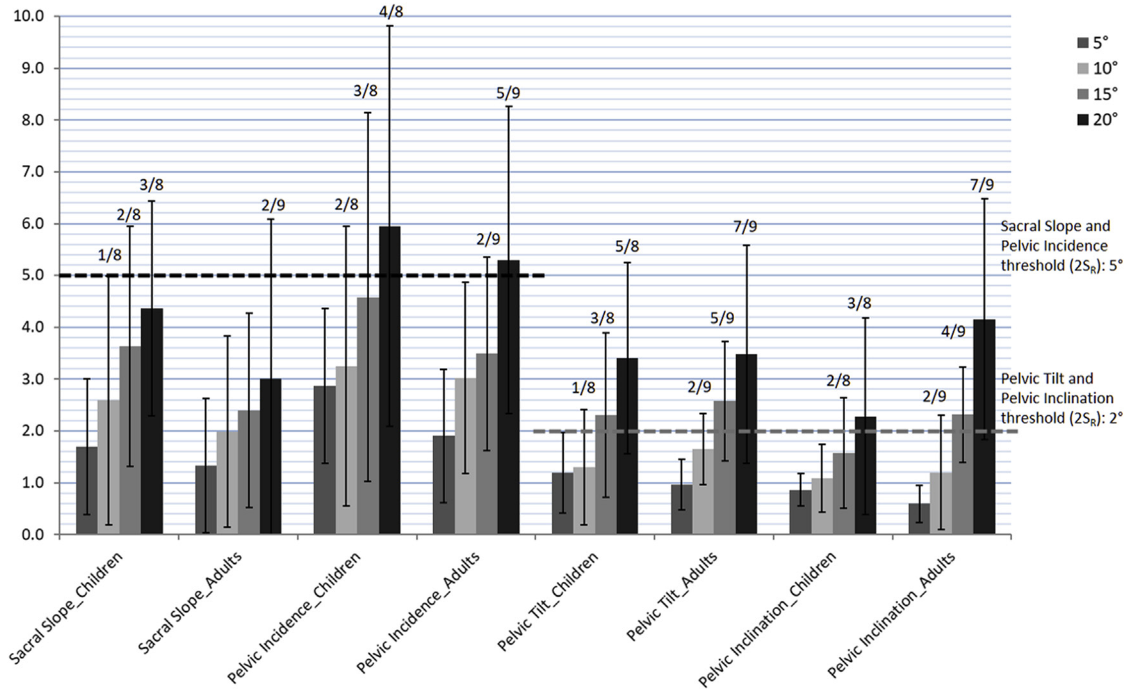

Figure 4 Mean biases (and SD) of each parameter at 5°, 10°, 15° and 20° of axial rotation relatively to the 0° of axial rotation position. Thresholds of acceptable errors (2SR) for each parameter are shown as horizontal lines. Number of cases where the threshold was exceeded is reported above each bar.

The bias on the bifemoral distance increased with the degree of axial rotation (1.2, 2.6, 4.1, and 5.5mm for 5°, 10°, 15°, and 20° of axial rotation, respectively); however, the bias on pelvic thickness was constant and ranged between 0.1 and 0.2 mm for all axial rotation positions.

Predictive methods

A linear regression ($R2= 0.835$, $p<0.001$) was obtained, for both children and adults, between the axial rotation position and the bifemoral distance normalized to the sagittal pelvic thickness:

$$\text{Axial rotation position } (^\circ) = -0.32+29.15\times(\text{bifemoral distance/sagittal pelvic thickness})$$

The normalized coefficient of the normalized bifemoral distance was $\beta=0.91$ ($p<0.001$) and the root mean square of errors (RMSE) = 2.90°. The graph representing the linear regression equation with its 95% CIs as well as the one representing the standardized residuals on the values of axial rotation predicted by the linear regression are presented in Fig 5.

Discussion

Treatment of spinal deformities requires restoration of both frontal and lateral spinal alignment. Pelvic parameters have become essential when assessing sagittal malalignment because of their strong relationship with spinal curvatures.[4] Accurate evaluation of pelvic parameters requires proper patient positioning during lateral radiograph acquisition. This study evaluated the effect of axial rotation on sagittal pelvic parameters measured on simulated lateral pelvic radiographs reconstructed from the pelvic helical CT examinations of eight children and nine adults. A regression formula was suggested to estimate the axial rotation from a lateral pelvic radiograph.

The ICC values on intra- and interobserver variability obtained in the present study were similar to those published previously.[17–19] Although most authors reported the ICC in order to assess the intra- and interobserver reliability of the radiological parameters, the SR was also calculated in order to report angular values of reliability. As reported by Bland and Altman,[20] correlation coefficients, from which the ICC is derived, are not the most appropriate index of agreement between repeated measurements. The repeatability coefficients would allow the calculation of the 95% confidence interval (2SR), which could be used in clinical practice to determine a threshold above which differences would be clinically significant and not due to measurement errors.

Only one study explored the effect of axial rotation of the patient on sagittal pelvic parameters.[19] The authors conducted measurements on only one phantom (an adult cadaveric female pelvis) and did not evaluate the repeatability of their measurements at each axial rotation position. To the authors' knowledge, the present study is the first to evaluate the reliability of sagittal pelvic parameters in the presence of axial rotation of patients during pelvic lateral radiograph acquisition in both adults and children.

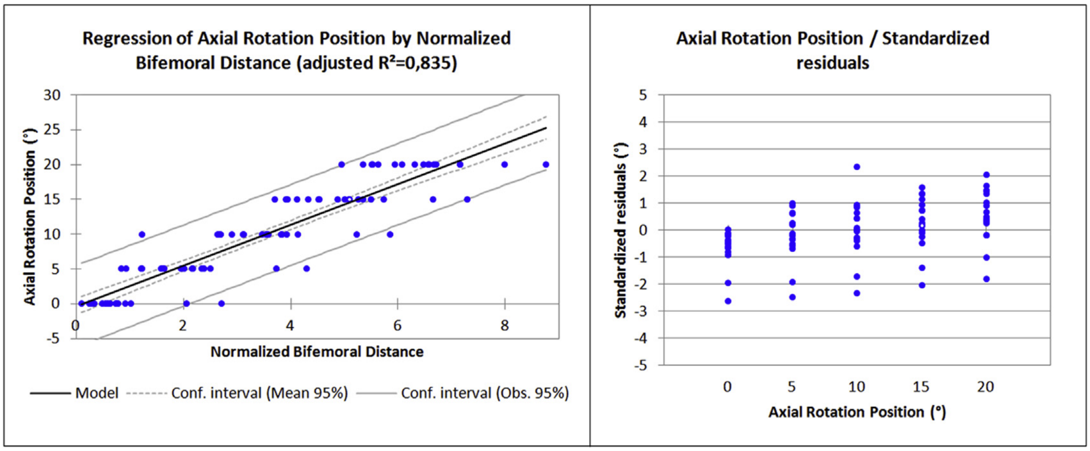

Figure 5 Left: Linear regression to predict axial rotation of the patient during acquisition of lateral pelvic radiographs, based on bifemoral distance normalized to sagittal pelvic thickness. Right: Standardized residuals on the values of axial rotation predicted by the linear regression, as a function of the exact values of axial rotation.

Results reported in the current study (Fig 3) demonstrate that reproducibility deteriorates when the axial rotation of the pelvis increases. This applies to both children and adults. Moreover, it was noted that the reproducibility of the parameters did not differ between adults and children.

Although it was expected that the bias on bifemoral distance increase with the axial rotation of the patient, the present study also reveals that the bias on the remaining parameters (Fig 4) increased with this rotation, except for sagittal pelvic thickness, whose bias remained constant. This can be explained by the fact that this parameter consists of the measurement of a line that is close to vertical, and therefore, is not affected by the axial rotation of the patient.

Even though there were no statistical differences on the biases between the children and adult groups, it was noteworthy that the biases and their variances were consistently higher in the children's group. The accepted threshold of error on each parameter was set as the 2SR (approximating the 95% CI) obtained at 0° of axial rotation. In a large proportion of cases, this threshold of error was exceeded at 15° of axial rotation for all parameters shown in Fig 4; however, this threshold was even exceeded at 10° of axial rotation in some of the cases. Thus, sagittal pelvic parameters could be considered as reliable only if the axial rotation of the patient during radiograph acquisition was inferior to 10°.

The study conducted by Tyrakowski *et al.*[19] suggested that the limit of acceptable axial rotation is 35° based on a threshold of 6° of acceptable error that had been previously published in the literature.[21] In the present study, the threshold value for acceptable error was set at 5° for pelvic incidence and sacral slope, and 2° for pelvic tilt and pelvic inclination, based on the interobserver reproducibility that was calculated at 0° of axial rotation. Moreover, the suggested limit of 10° of acceptable axial rotation in the present study was based on a population of eight children and nine adults, while the use of only one subject in the study of Tyrakowski *et al.* limits the possibility of generalization of their results.

Malpositioning of the patient during radiograph acquisition causes a distortion of the pelvis on a lateral projection. The incorporation into clinical routine of recent developments of biplanar radiographs and the corresponding three-dimensional (3D) reconstruction of skeletal segments allows the correction of measurement errors caused by such distortions. Indeed, in a recent study, 3D reconstruction of the pelvis using biplanar X-rays was shown to be more accurate (decreased bias and increased reproducibility) in the calculation of pelvic parameters in the presence of axial rotation compared to 2D measurements.[22] For instance, pelvic tilt had a bias of 1.3° and a SR of 1.5° at 20° of axial rotation using 3D reconstructions (versus 3.5° and 2.1°, respectively, in the present study); however, because of the limited accessibility to 3D reconstructions from biplanar X-rays, lateral X-rays are still extensively used for postural assessment. Therefore, it was essential to estimate the effect of malpositioning of the patient on radiological pelvic parameters measured on lateral X-rays. It was shown in the current study that axial malpositioning exceeding 10° significantly biases the measurement of pelvic parameters.

This finding led the authors to search for a method to estimate the axial malpositioning of the patient from the lateral radiograph. Thus, a linear regression was established based on the bifemoral distance normalized relatively to the sagittal pelvic thickness, in order to correct radiographic enlargement. The obtained R2 value (0.835), the level of significance of Fisher's test ($p<0.001$) and the RMSE (2.9°) were highly satisfactory. Thus, this equation could be used in clinical practice as a tool for the estimation of axial rotation on any given lateral pelvic radiograph. Therefore, considering the previous results on the level of biases when axial rotation exceeds 10°, if the physician were to calculate an axial rotation equal or superior to this value, the radiograph should be repeated with correct patient positioning.

Although standard radiographs are generated with a certain degree of enlargement, the suggested formula would still be applicable for any lateral radiograph as the distance is normalized, and therefore, independent of the value of the enlargement factor, which occurs similarly in the vertical and horizontal directions due to conical X-ray projection.

Another method developed by Tyrakowski *et al.* to estimate the axial rotation of the patient during X-ray acquisition based on the measurement of the bifemoral distance on both lateral and frontal radiographs was reported previously[19]; however, this method would rarely be applicable in clinical practice as it necessitates frontal radiographs acquired in a calibrated environment, simultaneously with the corresponding lateral ones. Therefore, the regression formula established in the present study would be easier to use in clinical practice.

The major limitation of the present study is linked to the fact that the simulated radiographs were reconstructed from pelvic CT images, which were performed on patients in the supine position. Although the standard standing position of patients, during conventional lateral full-spine radiography, was not respected, the DRR technique used in the present study is innovative in surpassing the ethical constraint of exposing patients to multiple radiographs at different axial rotation positions, especially applicable in children. Another limitation of the present study could be the relatively small number of subjects.

In conclusion, this study revealed that the reproducibility of sagittal pelvic parameters deteriorates when the axial rotation of the patient increases. Biases on clinical parameters exceed the acceptable values when the axial rotation reaches 10°. A regression formula was suggested in order to calculate axial rotation of the patient during X-ray acquisition based on the measurement of two parameters on the lateral radiograph. This formula, which applies to both children and adults, would thus be used in clinical practice in order to estimate the axial rotation of patients during radiograph acquisition, and consequently, allow physicians to discard any radiographs where the calculated rotation was $\geq 10°$.

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