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ORIGINAL ARTICLE

Pelvis radiographs in children with cerebral palsy: effects of patient positioning on calculating migration percentages

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Abstract

Background Hip displacement in children with cerebral palsy (CP) is monitored by measuring migration percentage on anteroposterior pelvis radiographs. However, proper positioning for radiography in children with spasticity is difficult. The reliability and accuracy of migration percentage as a function of patient positioning is unknown.

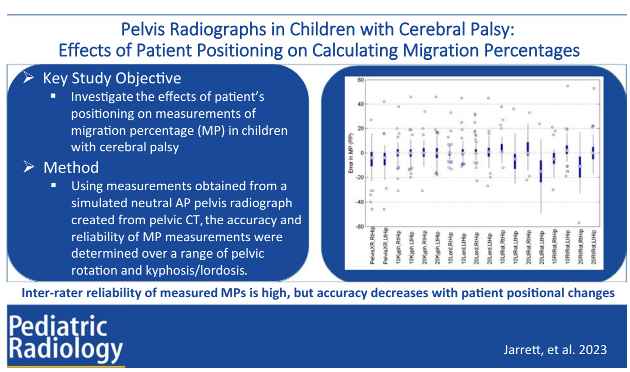
Objective To determine the effects of patient positioning on migration percentage measurements in children with CP.

Materials and methods We identified children with CP (≤18-year-old) with pelvis CT and anteroposterior pelvis radiograph obtained <6 months apart (10/2018–11/2021). Digitally reconstructed radiographs were generated from each pelvis CT, to simulate nine different patient positions: neutral; 10° and 20° lordosis and kyphosis; and 10° and 20° right rotation and left rotation. Two radiologists measured migration percentages from the simulated and real pelvis radiographs. We used Spearman's rho to assess inter-rater reliability, and Wilcoxon signed rank test to determine statistical significance.

Results We studied sixty-three children (male=41; median age=8 years; range=4–18 years). The two radiologists' migration percentage measurements were highly correlated with each other across all simulated and real radiographs (Spearman's rho=0.86–0.99, $P<0.01$). For both readers and hips, migration percentages measured from real radiographs were significantly different from those measured from neutral simulated radiographs ($P<0.01$), with median absolute difference=5–6 percentage points (PP) and interquartile range (IQR)=9–12 PP. When comparing migration percentage measurements from neutral simulated radiographs to those in kyphosis/lordosis and right/left rotations, median absolute differences were 2–4 PP (IQR=3–8 PP) and 4–15 PP (IQR=6–17 PP), respectively.

Conclusion Inter-rater reliability of measured migration percentages is high, but accuracy decreases with patient positional changes.

Graphical abstract



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Introduction

Cerebral palsy (CP) is the most common physical disability in children [1, 2]. The disorder is characterized by primary motor abnormalities that are often accompanied by intellectual disabilities, communication difficulties, and behavioral challenges. Children with CP have extensive orthopedic problems, including hip displacement with an estimated population prevalence of 35% [3, 4]. Their lifetime risk of hip displacement progressing to hip dislocation is 15–20% [5]. Hip dislocation can cause significant pain, severe contractures, leg deformity, and scoliosis; therefore, minimizing hip displacement is key to reducing morbidity and improving health related quality of life [6]. To this end, hip surveillance imaging programs for children with CP have been developed to monitor hips every 6–12 months according to functional level.

Reimer's migration percentage is the most commonly measured index performed on an anteroposterior (AP) pelvis radiograph [7–12]. Migration percentage measures the percentage of the femoral head that is laterally uncovered by the acetabulum. This metric plays an important role in guiding treatment for children with neuromuscular hip subluxation. Specifically, preventive surgery is indicated when migration percentage is >30%, and reconstructive surgery is indicated when migration percentage is >50% [13]. When migration percentage is >90%, the hip is considered dislocated; if in this position for a prolonged period, the femoral head becomes unreconstructible, and salvage surgery is indicated [5, 12]. Studies have reported a high inter- and intra-reader reliability in measuring migration percentages from pelvis radiographs in children with CP [14, 15]. However, although reliability is an important factor in the assessment of migration percentage's clinical utility, accuracy is an even more important factor, in particular when considering the positional challenges seen in children with CP and spasticity. Studies in adults and cadavers with morphologically normal hips have shown that common scalar metrics of the hips based on radiography (such as acetabular angle, acetabular version, and anterosuperior acetabular coverage) are prone to large errors with simple and modest changes in patient positioning [16–18]. This is highly relevant when imaging children with CP, as proper patient positioning is often difficult in this population due to spasticity, torsional malalignments, and resultant hip flexion and adduction contractures. To date, the impact of positioning on the accuracy of migration percentage measurements in children with CP has not been determined.

To address this important knowledge gap, this study investigated the effects of patient's positioning on measurements of migration percentage in children with CP. Specifically, in our study, we systematically varied the patient's position and analyzed its effect on migration percentage measurements. Using measurements obtained from a simulated neutral AP pelvis radiograph as the reference standard, the accuracy and reliability of migration percentage measurements were determined over a range of pelvic rotation and kyphosis/lordosis. Positions were simulated by digitally reconstructed radiographs created from pelvis CTs.

Materials and methods

Our institutional review board approved this retrospective study (protocol number IRB-P00041217). The study was compliant with the Health Insurance Portability and Accountability Act, and informed consent was waived.

Study population

We systematically conducted a computerized text search of the image archive at our large tertiary children's hospital to identify pelvis CTs performed per our protocol to assess hip/proximal femoral morphology and version (as detailed below), in the period between 10/2018 and 11/2021. The inclusion criteria were (1) children ≤18 years old, (2) a diagnosis of CP [19], and (3) an AP pelvis radiograph performed within 6 months of the pelvis CT. Only one paired AP pelvis radiograph and pelvis CT per child was included in the database. If a child had more than one pelvis CT during the study period, only the first CT was included in the database as subsequent CTs were often performed for post-surgical evaluation. In cases where there were multiple pelvis radiographs, the one performed closest in time to the CT was included in the database. There were no additional exclusion criteria.

Pelvis radiograph protocol

AP pelvis radiographs were acquired using digital radiographic systems (DigitalDiagnost, Philips Healthcare, Andover, MA), and were performed according to the American College of Radiology guidelines [20]. The tube voltage (kVp) and current-time (mAs) varied as a function of patient age and size, with typical ranges of 70–80 kVp and

2.5–15 mAs, respectively. To minimize geometric distortion and magnification, the radiographs were obtained on the tabletop with beam centering. To ensure proper positioning of the patient, standardized hip surveillance recommendations were followed [21]. Specifically, we obtained the radiographs with the child in supine position. To prevent internal or external rotation of the hips, the legs were rotated so that the patellae were facing straight upward, parallel to the imaging plate. To minimize tilt of the pelvis related to lordosis or kyphosis of the lumbar spine, padding was placed under the patient's pelvis and the knees to flatten the curvature of the spine.

Pelvis CT protocol

All patients in this study had a pelvis CT performed using the protocol to assess hip/proximal femoral morphology and version, as described below. Studies were performed using dual energy Siemens Somatom Force scanner (Erlangen, Germany). Weight-adjusted kVp (with reference kVp of 100 and 120 for patients <55 kg and ≥55 kg, respectively) was utilized, as well as automated tube current modulation (with quality reference mAs of 150 and 40 for patients <55 kg and ≥55 kg, respectively). Dual source scanning was employed with helical pitch of 3. The anatomical coverage of the pelvis CT protocol was from the iliac crests down to the knees. The extended imaging field-of-view to include the femurs and the knees was to enable simultaneous calculating of femoral version.

Simulated pelvis radiographs

For each CT, we used a 3D workstation with multi-planar reconstruction capabilities (Synapse, Fujifilm, Tokyo, Japan) to generate a simulated pelvis radiograph, based on average intensity projection. Each simulated pelvis radiograph was oriented into nine different positions (neutral, 10° and 20° lordosis, 10° and 20° kyphosis, 10° and 20° right rotation, and 10° and 20° left rotation) to simulate modest and realistic changes in patient positioning. Neutral position was defined by (1) horizontal alignment of the ischial tuberosities, (2) vertical alignment of the middle of the sacrococcygeal joint and the middle of the symphysis, and (3) vertical alignment of the symphysis and the anterior superior iliac spine [22–24] (Fig. 1). As the simulated pelvis radiographs in neutral position correspond to optimal patient position (without any tilt, lean, or rotation), we expect measurements made from these radiographs to be the most accurate. Therefore, in the absence of an independent ground truth, we considered migration percentages measured in neutral position as the reference standard for comparison.

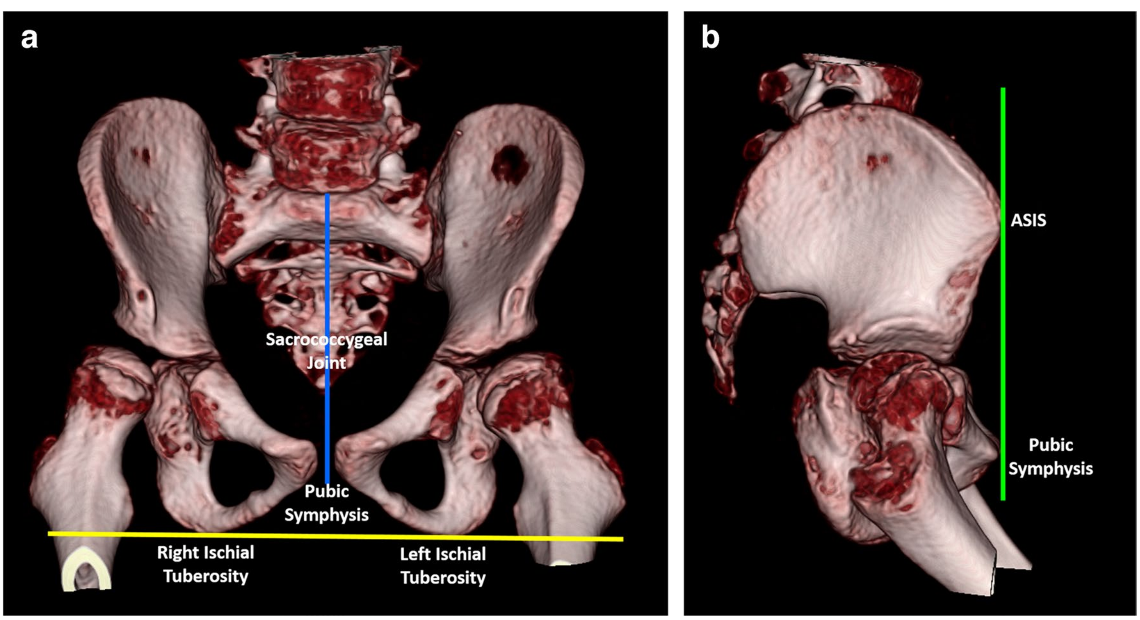

Fig. 1 Two 3D models of the pelvis generated from a CT performed on an 8-year-old boy with cerebral palsy. The two models were from the frontal (**a**) and right lateral (**b**) perspectives. Neutral position was defined by horizontal alignment of the ischial tuberosities (yellow horizontal line); vertical alignment of the middle of the sacrococcygeal joint and the middle of the symphysis (blue vertical line); and vertical alignment of the symphysis and the anterior superior iliac spine (ASIS) (green vertical line)

Image interpretation

Two readers (D.J. and A.T.), both pediatric musculoskeletal radiologists with comparable clinical experience (12–13 years post-fellowship), independently measured the migration percentages from the simulated pelvis radiographs in all nine positions, and from the real AP pelvis radiographs (Fig. 2). For each hip, migration percentage was measured by drawing three lines perpendicular to Hilgenreiner's line and placing them at the medial margin of the femoral head, lateral margin of the acetabulum, and lateral margin of the femoral head. Migration percentage is defined as the distance between the lateral margin of the acetabulum and the femoral head divided by the distance between the medial and lateral margins of the femoral head, then multiplied by 100 to convert to percentages. In patients with incomplete femoral head ossification, with eccentric ossification nucleus, the medial margin of the proximal femoral metaphysis was used as a substitute for the medial margin of the femoral head. All the measurements were made using the built-in electronic measurement tool within the picture archiving and communication system (Synapse, Fujifilm, Tokyo, Japan).

Statistical analyses

Spearman's rho, and for comparison, Lin's concordance correlation coefficient (CCC), and Bland-Altman analysis were used to quantify reader agreements. The Wilcoxon signed rank test for paired samples was used to statically compare measurements. Median and interquartile range (IQR) were estimated as summary statistics. As the unit for migration percentage is percentage (%), median absolute differences and IQR range were reported in percentage points (PP). Statistical significance was set at alpha=0.05, and estimated *P*-values were adjusted for the False Discovery Rate [25], given multiple comparisons of migration percentages from different positions. All statistical analyses were conducted using the software MATLAB R8.3 (MathWorks, Natick, MA).

Results

Study cohort characteristics

Our search resulted in a dataset of paired CT and pelvis radiograph from 63 children (male=41, female=22). Median chronological age at the time of the pelvis CTs was 8 years (IQR=6 years; range=4–18 years). The median time interval between a child's pelvis CT and pelvis radiograph was 76 days (range of 0 to 178 days, IQR=73 days). Based on the simulated neutral radiographs, the range of measured migration percentage was 0–100% for both Reader 1 and Reader 2.

Reader agreement

The two readers' right and left hip migration percentage measurements were highly correlated with each other across all simulated pelvis radiographs in all nine positions, as well as the real AP pelvis radiographs (rho=0.86–0.99, $P<0.01$). Both the CCC (Online Resource 1) and Bland-Altman analysis (Fig. 3) showed high correlation of these measurements as well. Inter-reader variability was assessed by comparing migration percentage measurements made by the two readers using the simulated pelvis radiographs in the neutral position (to eliminate any potential confounding effects of patient positioning). Median absolute difference was 3 PP (IQR=4 PP). We also compared readers' measurements based on the actual AP pelvis radiographs. Median absolute difference between readers was 3 PP (IQR=4 PP). Additional details on reader agreement in real radiographs and simulated radiographs are provided in Table 1. In addition, the scatterplot in Fig. 4 shows the linear relationship between the two readers' measurements. Overall, there was consistently high inter-reader reliability in migration percentage measurements, independent of patient positioning. Also, variability between reader measurements remained fairly consistent over the range of migration percentage.

Accuracy of migration percentage measurements

We compared migration percentage measurements made on the simulated AP radiographs in neutral position (i.e., the clinical imaging reference standard) with those measurements made on the real AP pelvis radiographs (with unknown patient position). Median (IQR) of the absolute differences was 5 PP (11 PP) for Reader #1 and 6 PP (9 PP) for Reader #2. For both readers and both hips, migration percentages measured from the AP pelvis radiographs were significantly different from those measured from the simulated pelvis radiographs in neutral position ($P<0.01$).

Study of patient position

To assess the sensitivity of migration percentage measurements to differences in patient position, we compared migration percentages derived from the simulated pelvis radiographs in neutral position to those in the eight other positions: (a) those derived from the right/left pelvic rotation (×4) and (b) those derived from pelvic tilt with kyphosis/lordosis (×4). Median absolute difference between readers' measurements was 4–15 PP (IQR=6–17 PP) for changes in rotation (with larger numbers corresponding to 20° rotation)

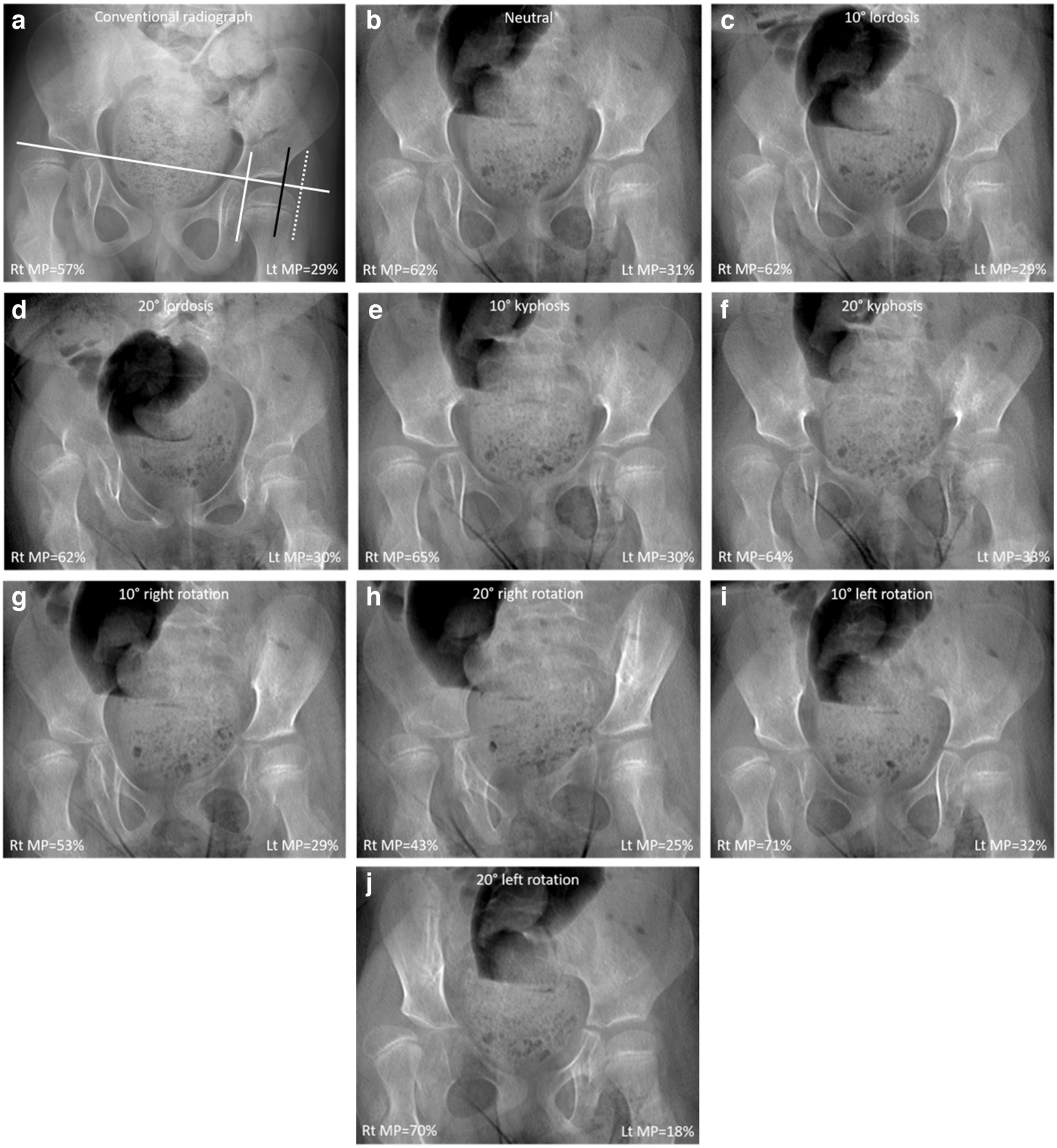

Fig. 2 Six-year-old male with cerebral palsy. The real anteroposterior (AP) pelvis radiograph of this patient with the migration percentages (MPs) of both hips are shown in the bottom corners of (**a**). Migration percentage measurement technique is illustrated for the left hip. The distance between the lateral acetabular margin and lateral femoral head margin (dotted white line to black line) is divided by the distance between the lateral and medial margins of the femoral head (dotted white line to solid white line). Using 3D workstation with multi-planar reconstruction capabilities, this patient's pelvic CT was used to create a digitally reconstructed radiograph in the AP projection. The simulated radiograph was reoriented into nine different patient positions (**b**)–(**j**). The migration percentages for one reader of both hips in neutral (**b**), 10° lordosis (**c**), 20° lordosis (**d**), 10° kyphosis (**e**), 20° kyphosis (**f**), 10° right rotation (**g**), 20° right rotation (**h**), 10° left rotation (**i**), and 20° left rotation (**j**) are shown in the bottom corners of each image

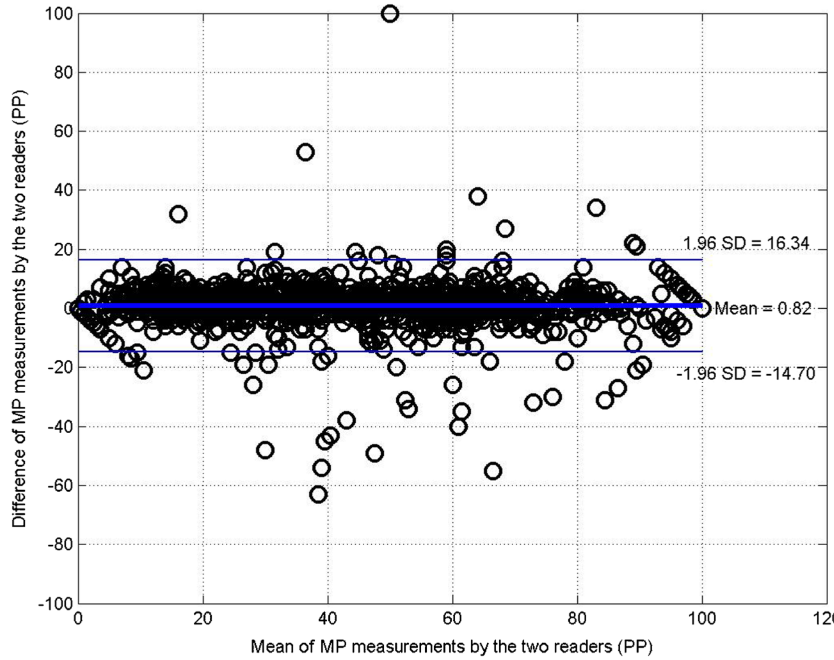

Fig. 3 Bland-Altman plots comparing migration percentage measurements generated by the two readers. The mean bias was 0.82 percentage points (PP), and the standard deviation was 7.92 PP. The limits of agreement range from −14.70 to 16.34 PP

and 2–4 PP (IQR=3–8 PP) for changes in kyphosis/lordosis. To further understand the effects of patient rotation, we performed a focused analysis of 20° right/left rotation. This analysis showed that right rotation had a relatively larger effect on migration percentage measurements of the right hip than the left hip, with median absolute difference of 12–13 PP (IQR 15–16 PP) versus 5 PP (IQR 6–8 PP), respectively. In contrast, left rotation had a relatively larger effect on

Table 1 Reader agreements of the migration percentage measurements, when utilizing real and simulated anteroposterior pelvis radiographs.

	Laterality	Spearman's rho		Median absolute difference (PP)	IQR (PP)
		Rho	*P*-value		
Anteroposterior pelvis radiograph	Right	0.94	<0.01	3	4
	Left	0.97	<0.01	3	4
Simulated pelvis radiograph • Neutral	Right	0.97	<0.01	3	4
	Left	0.86	<0.01	3	5
Simulated pelvis radiograph • 10° kyphosis	Right	0.98	<0.01	4	4
	Left	0.98	<0.01	2	3
Simulated pelvis radiograph • 20° kyphosis	Right	0.97	<0.01	3	5
	Left	0.98	<0.01	3	5
Simulated pelvis radiograph • 10° lordosis	Right	0.98	<0.01	2	4
	Left	0.99	<0.01	3	3
Simulated pelvis radiograph • 20° lordosis	Right	0.94	<0.01	2	4
	Left	0.93	<0.01	3	6
Simulated pelvis radiograph • 10° left rotation	Right	0.98	<0.01	4	5
	Left	0.88	<0.01	2	3
Simulated pelvis radiograph • 20° left rotation	Right	0.99	<0.01	3	4
	Left	0.90	<0.01	3	4
Simulated pelvis radiograph • 10° right rotation	Right	0.98	<0.01	3	5
	Left	0.98	<0.01	2	3
Simulated pelvis radiograph • 20° right rotation	Right	0.97	<0.01	4	5
	Left	0.96	<0.01	3	4

IQR, interquartile range

PP, percentage points

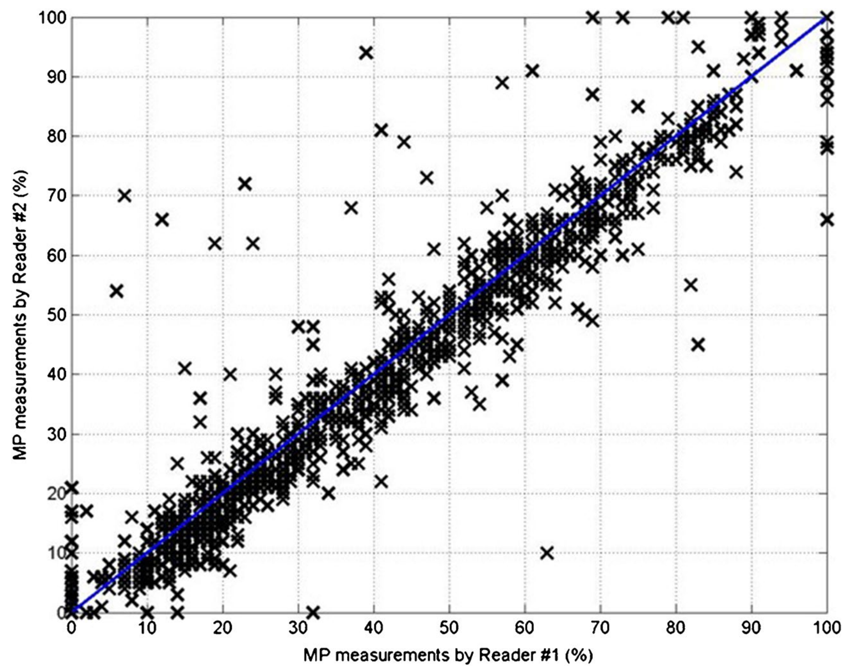

Fig. 4 Scatterplot comparing the migration percentage measurements by the two readers. This plot contains 1260 data points. The solid blue line is the identity line where the two readers' measurements are the same. Substantial majority of the data points hover around the identity line, indicating high inter-reader reliability

migration percentage measurements of the left hip than the right hip, with median absolute difference of 12–15 PP (IQR 15–17 PP) versus 5–6 PP (IQR 9–11PP). Thus, migration percentage measurements were more sensitive to ipsilateral rotations and less so to contralateral rotations of the hips. Summary statistics on measurement deviations from the radiologic reference standard at each investigated patient position are provided in Table 2.

Measurement errors as a function of patient positioning (relative to the radiologic reference standard of a neutral pelvis position) are shown in the boxplots in Fig. 5. Right/left patient rotations had the largest effect on the accuracy of the migration percentage measurements, particularly with 20° ipsilateral rotation, resulting in a decrease in measured migration percentage (negative error).

Discussion

Using a combination of real and simulated radiographs, this study investigated the reliability and accuracy of migration percentage measurements as a function of patient position. The primary finding of the study is that inter-reader variability and patient's suboptimal positioning impact the migration percentage measurements made on the AP pelvis radiographs, with median deviations of 5–6 PP from the reference standard. These migration percentage deviations are substantial and increase uncertainty in the detection of disease progression, given that a 10-percentage point increase in migration percentage is empirically considered clinically significant progression of disease, necessitating treatment intervention. We also found that migration percentage measurement errors may be greater with right/left rotations of the pelvis than with comparable kyphosis/lordosis. More specifically, errors in migration percentage measurements were higher with ipsilateral rotations of the pelvis and less so with contralateral rotations. Ipsilateral rotation resulted in an overestimation of femoral head coverage, or negative error in migration percentage compared to the reference standard. This is thought to be related to projectional artifact, and can subjectively be appreciated when comparing the appearance of the right hip in Fig. 1b versus Fig. 1i. With 20 degrees of rightward rotation, the lateral margin of the acetabulum projects more laterally over the right femoral head than it does in simulated neutral position.

Despite the high reader agreement of the migration percentage measurements across all simulated and real pelvis radiographs, there were still a small percentage of outliers. The etiology of these outliers are likely multifactorial. In particular, severe hip deformities and osteoporosis (often present in these patients) make the landmark points used to calculate migration percentage ambiguous and challenging to identify. Unfortunately, this is the practical reality of measuring migration percentages in this patient population.

Importantly, when comparing the migration percentage measurements from the real AP pelvis radiographs to our radiologic reference standard (the simulated neutral AP pelvis radiographs), the error in measurement and variability for each reader was higher than the inter-reader variability for migration percentage measurements. This data suggests that the differences in the migration percentages measured

Table 2 Parametric study of patient positioning, showing the difference (i.e., error) in migration percentage measurements after subtracting them from the gold standard (i.e., the migration percentages measured from the simulated pelvis radiograph in neutral position).

	Laterality	Reader #1		Reader #2	
		Median absolute difference (PP)	IQR (PP)	Median absolute difference (PP)	IQR (PP)
Anteroposterior pelvis radiograph	Right	6	12	6	9
	Left	5	10	6	11
Simulated pelvis radiograph • 10° kyphosis	Right	3	5	4	6
	Left	3	6	2	3
Simulated pelvis radiograph • 20° kyphosis	Right	3	6	3	6
	Left	4	8	3	5
Simulated pelvis radiograph • 10° lordosis	Right	2	5	3	6
	Left	3	7	2	3
Simulated pelvis radiograph • 20° lordosis	Right	2	6	3	6
	Left	4	6	3	4
Simulated pelvis radiograph • 10° left rotation	Right	4	7	4	7
	Left	6	11	6	7
Simulated pelvis radiograph • 20° left rotation	Right	6	11	5	9
	Left	15	17	12	15
Simulated pelvis radiograph • 10° right rotation	Right	5	7	8	10
	Left	5	9	4	7
Simulated pelvis radiograph • 20° right rotation	Right	12	15	13	16
	Left	5	8	5	6

IQR, interquartile range

PP, percentage points

from the actual AP pelvis radiographs must be due to suboptimal, non-neutral patient positions.

It is well known that patient positioning on radiographs affects the perceived morphology of the hip, and the measured values for acetabular angles and coverage. However, to our knowledge, no prior study has assessed the accuracy and reliability of migration percentage measurements made on AP pelvis radiographs in children with CP as it pertains to changes in patient positioning. Understanding the effects on patient positioning on radiographic measurements is of particular importance when treating children with CP. In this population, accurate assessment of hip alignment is needed to time surgical intervention; and obtaining consistent, well-positioned radiographs of the pelvis and hips in these patients, without tilt or rotation, is often challenging. As such, the results of our study bridge an important knowledge gap in the literature.

The key to the success of this investigation was the pelvis CT, which we used to digitally reconstruct simulated pelvis radiographs in various positions for our study. Using this same approach, future areas of study could include analyses of the effects of patient position on other scalar metrics that we often used to characterize the hips (such as acetabular angle and version, and anterosuperior acetabular coverage). Furthermore, we will examine the effects of hip deformities (including coxa valga and hip flexion deformities) and other positional changes on these scalar metrics, which are particularly pertinent to our study cohort.

These results should be considered in light of the following limitations related to this retrospective study. Our cohort was biased toward children with severe neuromuscular hip displacement, as the most common indication for pelvis CT in our study cohort was pre-surgical planning. Nevertheless, these are the patients who are at highest risk of inaccurate migration percentage measurements because of suboptimal positioning. Second, we did not perform an assessment of other factors which may affect migration percentage measurements due to pelvic morphology, such as inherent pelvic asymmetry in patients with long standing dysplasia, varying effects of patient position in the setting of asymmetric or unilateral hip dysplasia, or the effects of coxa valga deformity. Nor did we assess the effects of other positional changes on the measurements of migration percentage, such as hip flexion or hip abduction/adduction. These are interesting areas for a future study. Third, we did not investigate intra-reader agreement. However, other studies have already reported high intra-reader reliability in migration percentage measurements [14, 15]. Fourth, the quality of the digitally reconstructed simulated pelvis radiographs is not the same as the real AP pelvis radiographs (with slightly lower resolution and contrast), though we did not feel that the diminished image quality made a substantial impact on our migration percentage measurements. Finally, we conducted this study based on a relatively small sample with the help of two pediatric musculoskeletal radiologists. A future study on a large patient

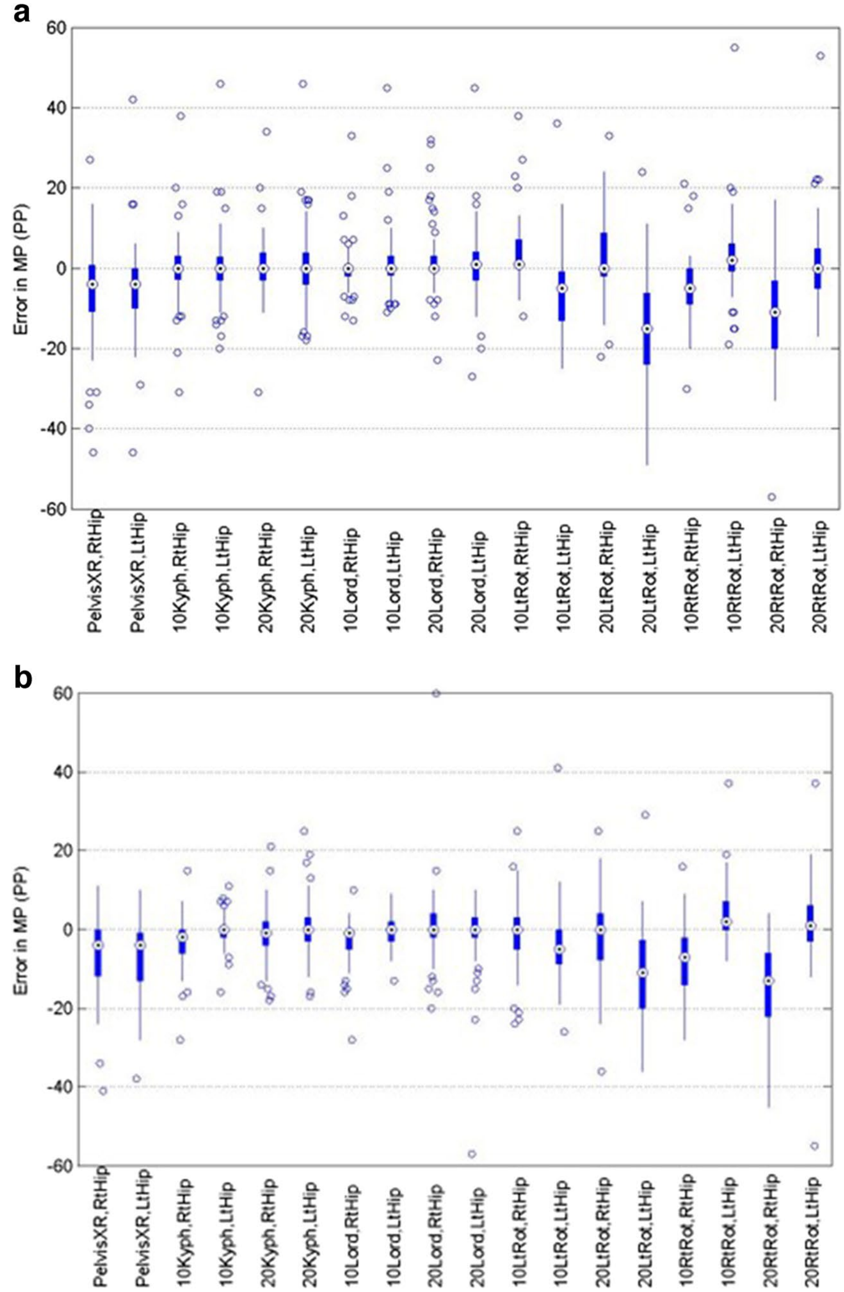

Fig. 5 Boxplot analysis of Reader #1 (**a**) and Reader #2 (**b**). The y-axis is the calculated migration percentages (MPs) for each position after subtracting the migration percentages from the neutral position. This difference or error is expressed in percentage points (PP). The x-axis consists of 18 sets of data, including the right hip (RtHip) and the left hip (LtHip) from the pelvis radiographs (PelvisXR) and the simulated radiographs in 8 different patient positions (10° kyphosis [10Kyph], 20° kyphosis [20Kyph], 10° lordosis [10Lord], 20° lordosis [20Lord], 10° left rotation [10LtRot], 20° left rotation [20LtRot], 10° right rotation [10RtRot], and 20° right rotation [20RtRot]). For each set of data, the median is denoted by a plus sign surrounded by an open circle. The edges of the thick blue bar (i.e. the box) indicate the 25th and 75th percentiles. The thin vertical lines (i.e., the whiskers) extend to the most extreme data points not considered outliers. The outliers are plotted individually using the open circle symbol

cohort using multiple readers with variable experience may provide more generalizable findings on the accuracy and sources of variability of migration percentage measurements.

Conclusion

Our results provide convincing evidence that migration percentages measured from AP pelvis radiographs have certain limitations when assessing hip displacement in children with CP. In particular, modest change in position may have a significant effect on the measurements of migration percentage, with range of error from 4 to 15 PP depending on patient position. This information should be taken into account when using the migration percentage for treatment planning. Therefore, it is important to consider alternative imaging modalities, such as CT or MRI, which may be more accurate diagnostic tools than radiographs to assess potential candidates for surgical intervention.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00247-023-05783-7.

Data availability The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

Code availability Not applicable

Declarations

Ethics approval IRB approved

Consent to participate IRB exempt status

Consent for publication IRB exempt status

Conflicts of interest None

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