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Evaluation of errors in measurements of infantile hip radiograph using digitally reconstructed radiograph from three-dimensional MRI

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ABSTRACT

Purpose: Plain hip radiograph is commonly used for the diagnosis of infantile acetabular dysplasia. Many infants are unable to maintain adequate position during radiography. Besides, the infantile hip is much smaller and has a higher cartilage component in the acetabulum and proximal femur compared with the adult hip. In this study, we developed a digitally reconstructed radiograph synthesized from magnetic resonance imaging (MRI) and investigated errors of hip radiographic measurements in different pelvic positions.

Patients and methods: MRI of both hips was performed in 10 patients (mean age 3.9 years). Three-dimensional (3D) bone models were created from MRI data. We tilted 3D pelvic bone models between 10° anteversion and retroversion and through 10° rotation on the affected and contralateral sides using 3D axes. Following this, we created digitally reconstructed radiographs in each pelvic position and calculated the acetabular index (AI), center-edge angle (CEA), migration percentage (MP), and teardrop distance (TDD).

Results: AI tended to increase with pelvic retroversion and did not change with pelvic rotation. CEA tended to decrease with pelvic retroversion and rotation on the contralateral side. MP increased with pelvic retroversion and rotation on the contralateral side. TDD did not change significantly with pelvic tilt and rotation.

Conclusions: Radiographic measurements of hip in infants were highly influenced by pelvic movement. AI was influenced by pelvic tilt; CEA and MP were influenced by both pelvic tilt and rotation. We need to keep in mind that infantile hip radiographs could have about ± 5° errors in AI and CEA.

1. Introduction

Developmental dysplasia of the hip (DDH) is a common musculoskeletal disease.[1–3] Infants with DDH often have acetabular dysplasia, which, if uncorrected, can lead to early degenerative joint disease in the long term. Surgical correction of acetabular dysplasia in infants has been widely performed to prevent future osteoarthritis.[4,5] Early and accurate diagnosis of hip dysplasia in DDH is important for treatment. Plain hip radiograph is commonly used for the diagnosis and evaluation of infantile acetabular dysplasia.[6–8] Computed tomography (CT) is not commonly used for evaluation of the infantile hip because children are highly sensitive to radiation. Magnetic resonance imaging (MRI) is also not widely used because of the requirement for sedation.

Radiographic measurements of acetabular dysplasia have been studied in detail in the past.[8,9] The acetabular index (AI), center-edge angle (CEA), migration percentage (MP), and teardrop distance (TDD) are usually measured for the diagnosis of infantile acetabular dysplasia. However, infants may not be able to maintain adequate position during radiography. Furthermore, the infantile hip is much smaller and has a higher cartilage component in the acetabulum and proximal femur compared with the adult hip. Radiographic measurements of the infantile hip are likely to be influenced by position, particularly by pelvic movements during radiography. There have been few studies that assessed the accuracy of the infantile hip radiograph and the previous reports had some discrepancies about the method of analysis and they investigated very low number of patients. In this study, we created digitally reconstructed radiograph (DRR) synthesized from MR images and three-dimensionally analyzed errors of radiographic measurements in different pelvic positions.

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2. Patients and methods

In this retrospective review of medical records from 2011 to 2016, we identified 10 infants with DDH treated at our institute. There were two male and 8 female patients. Nine patients had unilateral and one had bilateral dislocated hips prior to the initial treatment. The mean age at examination was 3.9 years (range 2.6–5.6 years). All patients underwent gradual reduction of dislocated hips using overhead traction or flexion and abduction continuous traction[10,11] at the initial treatment and plain MRI during follow-up. No patient had avascular necrosis and the deformity of femoral head. The study was approved by the institutional review board (ID: 15170).

During plain hip MRI, patients were placed in a supine position under sedation. MRI was performed using a 1.5T Philips Medical System (Philips Achieva, Best, The Netherlands). T1-weighted images were obtained in coronal planes using three-dimensional flash method and capture conditions were: TR 7.5 ms, TE 3.4 ms; thickness 1-mm-slice; matrix 512 × 512. Data were saved in the Digital Imaging and Communications in Medicine format. Reconstruction into 3D bone models of the pelvis and proximal femur (not including cartilaginous components) was performed using a 3D picture analysis volume analyzer software, SYNAPSE VINCENT (FUJI FILM, Japan).[12] 3D models were analyzed using original software (Orthopedics Viewer; Osaka University, Osaka, Japan). The anatomical axes were determined as follows[13]: the Y-axis was the reference line, joining both posterior superior iliac spines and pointing to the right; the Z-axis was the line connecting the origin and the midpoint of the right and left anterior superior iliac spine and pointing to anteriorly; the X-axis was perpendicular to both Y and Z axes. Point of reference was the midpoint of both anterior superior iliac spines.

We tilted the 3D pelvic bone models between 10° anteversion and retroversion and rotated between 10° right and 10° left using the anatomical axes. Following this, we projected the 3D bone model into XY plane and created digitally reconstructed anteroposterior radiographs of the hip in each position of the pelvis (Fig. 1a). Then we calculated the obturator foramina ratio, AI, CEA, MP, and TDD. The width and height of the obturator foramina were measured and the obturator foramina ratio (width/height) was calculated. The width of the obturator foramina was defined as the maximum length of the obturator foramina parallel to the Hilgenreiner's line. The height of the obturator foramina was defined as the maximum length perpendicular to the Hilgenreiner's line. AI was measured as the angle between the external roof of acetabulum and the Hilgenreiner's line, which unites the central points of the Y-shaped triradiate cartilage of both hips. CEA was measured as the angle between the center of the femoral head and the frontal external roof of the acetabulum. MP was measured by dividing the width of the femoral head metaphysis outside the acetabular edge by the total width of the femoral head metaphysis. TDD was the difference in the horizontal distance of both hips between the ossified femoral neck and the lateral margin of the pelvic teardrop.

To evaluate intra-reliability, each parameter was measured 3 times at intervals of 1 week. To evaluate inter-reliability, each parameter was measured by 3 orthopaedic surgeons. Intra- and inter-observer reliability were evaluated by the intra-class correlation coefficient (ICC). The ICC was 0.94–0.98 for AI, 0.91–0.94 for CEA, 0.92–0.97 for ICC of MP, and 0.95–0.99 for ICC of TDD.

3. Results

3.1. Obturator foramina ratio

The average obturator foramina ratio in the neutral position was 0.93 (range 0.61–1.21). Obturator foramina ratio tended to increase with pelvic anteversion and rotation on the affected side (Fig. 1b and c). The mean obturator foramina ratio was 0.76 at 10° pelvic retroversion, 1.26 at 10° anteversion, 0.7 on pelvic rotation on the contralateral side, and 1.09 on pelvic rotation on the affected side.

3.2. Acetabular index

The average AI with the pelvis in neutral position was 26.7° (range 14.9–40.9). AI changed significantly with pelvic tilt and tended to increase with pelvic retroversion (Fig. 2a). When the pelvis was tilted 10° backward, the mean error in AI was 4.6° (range 2.0–8.3). When the pelvis was tilted 10° forward, the mean error in AI was −3.9° (range −0.6 to −7.1). On pelvic rotation, AI did not change, being < 1° with 10° rotation (Fig. 2b).

3.3. Center-edge angle

The average CEA with the pelvis in neutral position was 21.6° (range 8.13–27.1). CEA changed during pelvic tilt and rotation and tended to decrease with pelvic retroversion and rotation on the contralateral side (Fig. 3). The mean error in CEA was −4.2° (range −2.0 to −7.6) with 10° pelvic retroversion and 4.9° (range 2.4–7.8) with 10° pelvic anteversion (Fig. 3a). The mean errors in CEA was 4.3° (range 0.9–9.6) with 10° pelvic rotation on the affected side and −6.2° (−2.2 to −15.9) with 10° pelvic rotation on the contralateral side (Fig. 3b).

3.4. Migration percentage

The average MP with the pelvis in neutral position was 21.5% (range 10%–38.5%). MP changed during pelvic tilt and rotation and tended to increase with pelvic retroversion and rotation on the contralateral side (Fig. 4). The mean error in MP was 4.7% (range 1.8%–10.9%) with 10° pelvic retroversion and −3.1% (range −1.5 to −5.1) with 10° pelvic anteversion. The mean error in MP was −5.6% (range −1.1% to −9.6%) with 10° pelvic rotation on the affected side and 7.5% (range 0–16.3) with 10° pelvic rotation on the contralateral side.

3.5. Teardrop distance

The average MP with the pelvis in neutral position was 5.2 mm (range 1.2–13.0). TDD did not change significantly with pelvic tilt and rotation (Fig. 5).

4. Discussion

The infantile hip is usually evaluated using plain anteroposterior hip radiograph. Infantile acetabular dysplasia is diagnosed using radiographic measurements such as AI, CEA, MP, and TDD. However, there have been few reports on the accuracy of infantile hip radiographs for this assessment. This is because of the difficulty in performing multiple radiographs in the varying positions to conduct a study because infants are relatively more sensitive to radiation. Portinaro et al.[14] investigated errors in AI on hip radiographs. In their post mortem study, four infants were placed supine, and serial radiographs were performed with the beam inclined at 5°–30° in the sagittal and cephalic planes. They reported that errors of 10° in AI can occur when pelvic flexion/extension was 20° from neutral position. Bom et al.[15] evaluated the influence of pelvic tilt and rotation using DRR from pelvic CT of a 3-month-old infant. They rotated and tilted whole CT volume digitally and mimicked pelvic rotation and tilt. They reported errors in AI ranging from −8.8°–4.5° with pelvic tilt and rotation up to 12°. There are some discrepancies in previous reports. In Portinaro's study, several hip radiographs were performed with beam inclination and rotation substituted for pelvic tilt and rotation. If patients were placed on the table with the pelvis in neutral position, the beam inclination and rotation corresponded to pelvic tilt and rotation. As it is difficult to place infants with the pelvis in a perfectly neutral position, any tilt of the pelvis may have caused some degree of rotation as well, and angle calculation may

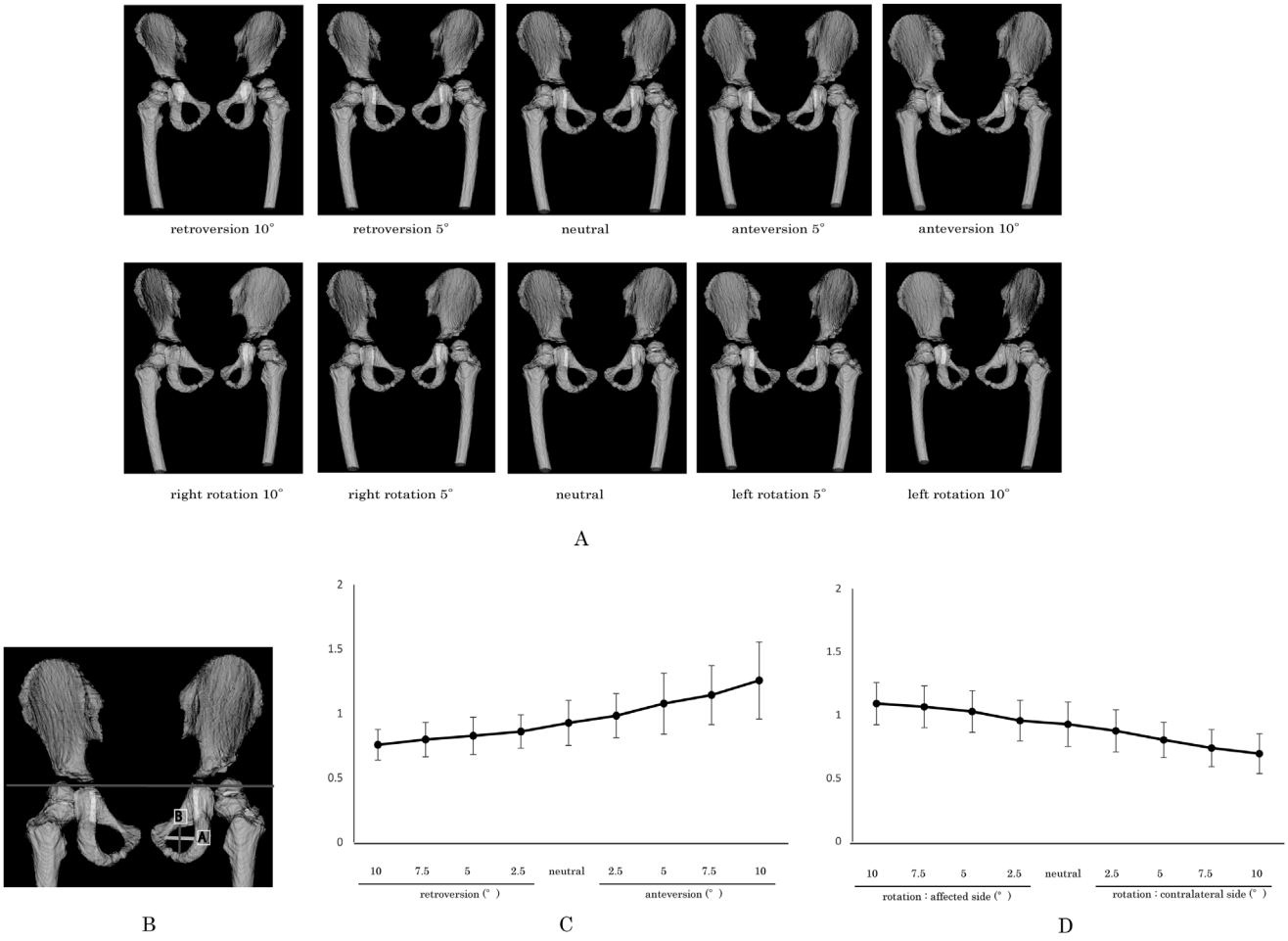

Fig. 1. A. Radiographic appearance with the different pelvic position.
B. Obturator foramina ration; width (A)/height (B).
C. Errors in Obturator foramina ration with the pelvic tilt.
D. Errors in Obturator foramina ration with the pelvic rotation.

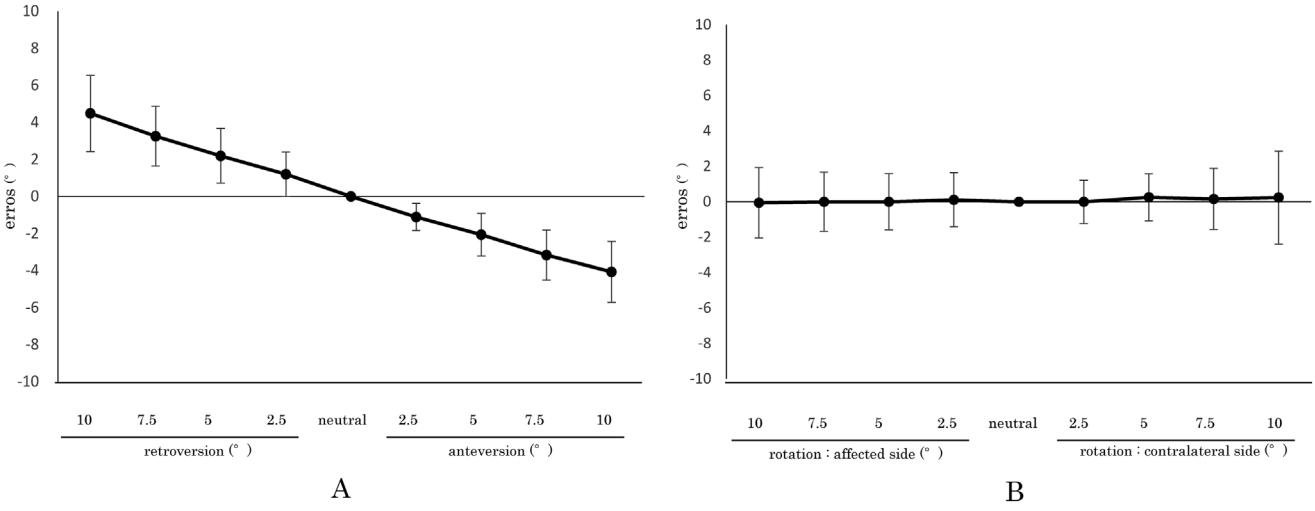

Fig. 2. Errors in AI. A. with pelvic tilt. B. with pelvic rotation.

have been inaccurate. In Bom's study, they created DRR three-dimensionally and evaluated in detail; however, they directly tilted and rotated the whole CT volume data. For this method to be accurate, it is necessary to assume the axes of CT volume coincides with the anatomical axes of the pelvis; however, in reality, axes of CT volume are different from those of the pelvis because they are strongly influenced by the posture at the time of shooting.

In adults, DRR synthesized from CT has been developed and the verification of radiographic measurements of the spine, pelvis, and foot has been investigated.[16–18] DRR of the hip has been studied,

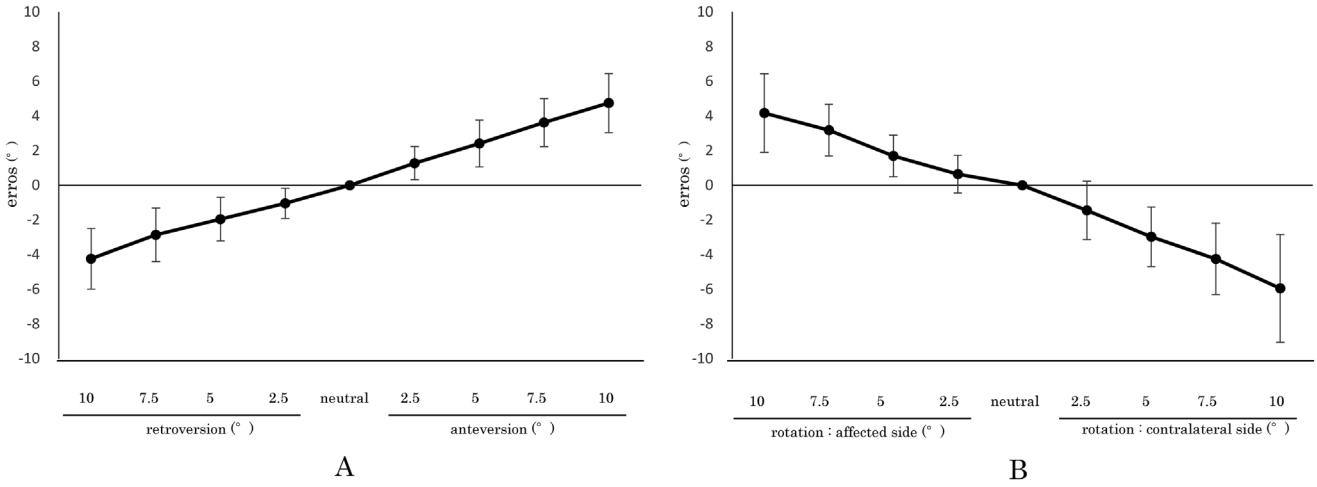

Fig. 3. Errors in CEA. A. with pelvic tilt. B. with pelvic rotation.

particularly in the total hip arthroplasty.[19,20] However, DRR from CT is not suitable for the infantile hip because of a high level of radiation. Rathnayaka et al.[21] compared the accuracy of 3D models from CT and MRI using the femur from cadavers and concluded that the accuracy of the 3D models from MRI was similar with that of CT-based models. Broeck et al.[22] reported that 3D models created from both CT and MRI had a high accuracy compared with actual measurements of cadaver tibia using an optical scanner. Therefore, our study utilized MRI, routinely performed during follow-up according to our protocol, for the management of DDH. We created DRR of hip synthesized from 3D MRI. Using DRR from MRI, we analyzed errors in radiographic measurements by digitally altering pelvic tilt and rotation mimicking patient movements during radiography. Radiographs of children are usually performed without sedation and hence, pelvic position during the procedure can easily change with body movements. It has become possible to verify the errors in hip radiograph by simulating body movement during radiography by precise pelvic tilt and rotation using the anatomical axes of the pelvis. In the clinical practice, excessive pelvic tilt and rotation may be noticed by the shape of the ilium and the obturator foramen in radiographs.[23–25] Usually pelvic rotation is easy to find, because the shape of the ilium and the obturator foramen is different on the right and left. However, it is often difficult to recognize when the pelvis is tilted. The shape of obturator foramen varies from individual to individual and when the pelvis is tilted, it is often difficult to notice because of lack of the difference on the right and left. Hence, we simulated a minimal pelvic movement of $< 10^{\circ}$ in this study. We observed an obturator foramina ratio of 0.7–1.26 during a 10° pelvic tilt; the obturator foramina ratio in neutral position was 0.61–1.21. These results indicate that a 10° pelvic tilt was often difficult to notice in the clinical practice.

Radiographic measurements such as AI, CEA, MP, and TDD have been reported to be important diagnostic and therapeutic indices. Especially, AI and CEA are commonly used for the diagnosis of hip dysplasia and to plan surgical treatment. The normal range of AI is usually $< 30^{\circ}$ and that of CEA is $> 20^{\circ}$. Our results show that AI tends to increase with pelvic retroversion. However, errors in AI had little influence on pelvic rotation. This result is not consistent with those of previous reports. This is because previous studies did not use the anatomical axes of the pelvis; rotation of the pelvis in the previous reports may have included pelvic tilt and rotation. CEA tended to decrease with pelvic retroversion and rotation on the contralateral side. In some cases, normal and abnormal values of CEA were recognized with pelvic tilt and rotation. MP also tended to increase with pelvic retroversion and rotation on the same side. TDD showed a slight tendency to increase with pelvic anteversion, but the difference of TDD between both hips had little change. These results show that pelvic retroversion caused worsening of acetabular dysplasia in AI; retroversion and rotation on the contralateral side caused worsening in CEA and MP. Importantly, AI could change from normal to abnormal values by a 10° pelvic tilt. CEA could change from normal to abnormal values by both 10° pelvic tilt

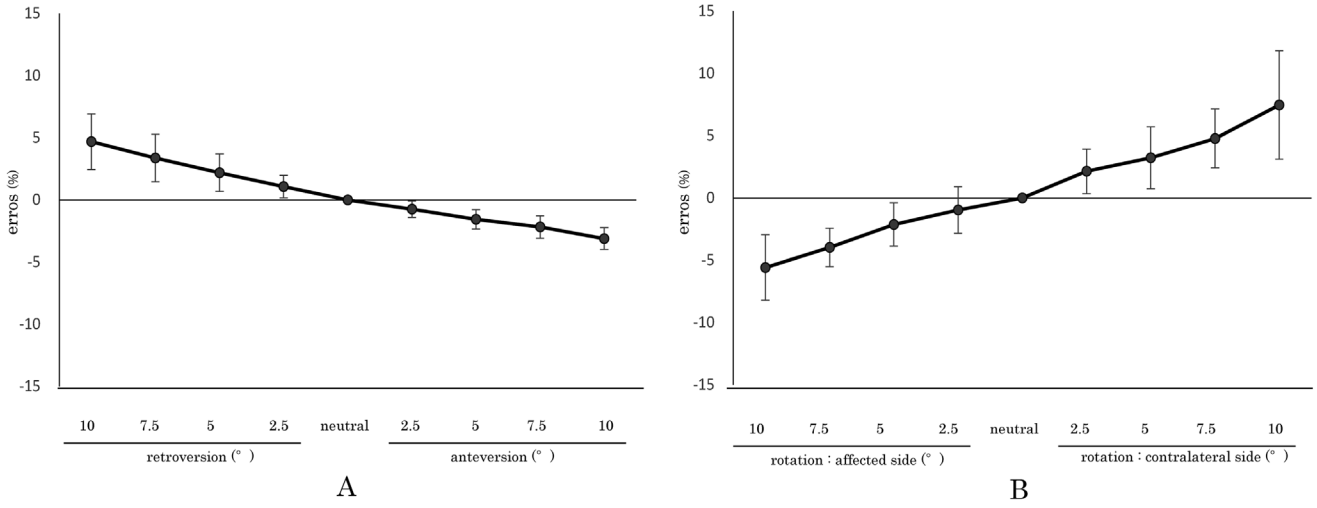

Fig. 4. Errors in MP. A. with pelvic tilt. B. with pelvic rotation.

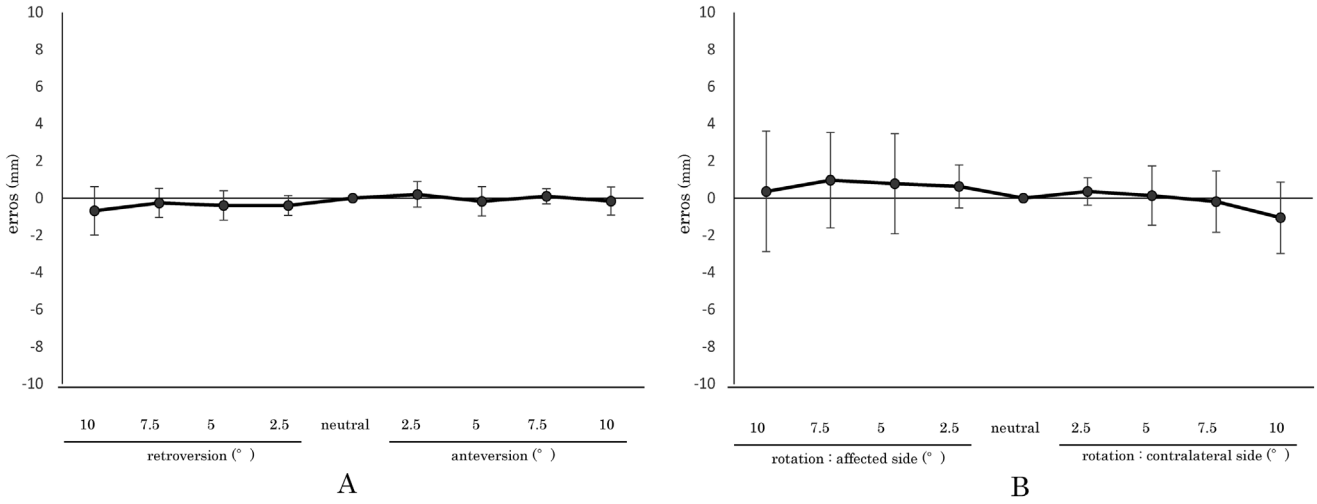

Fig. 5. Errors in TDD. A. with pelvic tilt. B. with pelvic rotation.

and rotation. AI and CEA have been widely used for the diagnosis of acetabular dysplasia and as criteria for surgical treatment such as pelvic osteotomy. Our results suggest that infantile hip radiographs are difficult to notice about the pelvic tilt and are highly influenced by pelvic movement. The diagnosis of infantile acetabular dysplasia should not be made with a single measurement. Even when we see the hip radiographs without right and left difference, we need to keep in mind that infantile hip radiographs could have some errors in AI and CEA. Multiple radiographic measurements on several radiographs may be required during follow-up.

We investigated the errors of infantile hip radiographic measurements using DRR from MRI imaging. Our study is limited by variation in the age of patients. We need to study a larger number of patients in various age groups and compare with actual radiographic images.

5. Conclusions

Radiographic measurements of hip in infants were highly influenced by pelvic movement. AI was influenced by pelvic tilt; CEA and MP were influenced by both pelvic tilt and rotation. The diagnosis of infantile acetabular dysplasia should not be made with a single measurement and we need to keep in mind that infantile hip radiographs could have ± 5° errors in AI and CEA. Multiple radiographic measurements on several radiographs may be recommended.

Conflicts of interest

None of the authors have any conflicts of interest of disclosures in relation to this work.

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