

Three-dimensional Morphologic Study of the Child's Hip: Which Parameters Are Reproducible?

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Abstract

Background Biplanar x-ray images obtained with patients in a standing weightbearing position allow reconstruction of three-dimensional (3-D) bone geometries, with lower radiation exposure than CT scans and better bone definition than MRI.

Questions/Purposes We determined the reproducibility of 3-D parameter values of the hips and pelves of healthy children, using biplanar x-ray images.

Methods We built 3-D models of the hips of 33 children without musculoskeletal problems: 10 subjects younger than 9 years and 23 who were 9 years or older. Three anatomic landmarks and nine hip and pelvic parameters were computed for each reconstruction. To determine the reliability of these landmarks and parameters, each bone was reconstructed four times by two independent observers, leading to a total of 264 reconstructions, and parameters were studied for the two age groups and compared between dancers and nondancers.

Results Taking into account all reconstructions, the interobserver reproducibility ranged from 2 to 4 mm for landmark positions or distance parameters, and 2° to 6° for angular parameters. The most reproducible point was the center of the femoral head (range, 0.2–17 mm). The distance between this center and its projection on the plane fitting the edge of the acetabulum, and the pelvic tilt were the most reproducible parameters.

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Conclusions Reproducible 3-D reconstructions of hips and pelves of children were possible using biplanar x-ray images, regardless of the children's ages. Although we report preliminary values for 3-D parameters in healthy children's hips, further work is needed to obtain direct validation of our parameters using CT reconstructions of cadaveric specimens to avoid high doses of radiation.

Introduction

Various measurements can be made on a plain radiograph of a child's pelvis. As the hip is a three-dimensional (3-D) structure, it is important to evaluate 3-D parameters with the hip in its functional standing position. Three-dimensional methods of imaging have disadvantages: MRI provides a low definition for bone and CT requires a high radiation exposure too great to be used in common practice with children. Moreover, neither of these two modalities can provide images with the patient in a standing functional position. The EOS® system (EOS Imaging®, Biospace Med, Paris, France) and associated software allow reconstruction of 3-D bone geometries, based on two biplanar x-ray images taken with the patient in a standing position [1, 3, 7]. This technique provides better bone definition than MRI and lower radiation exposure than CT. Moreover, the duration for acquisition of the radiographs is approximately 20 seconds for an entire body, which is faster than CT and MRI, thus is particularly suited for children.

We applied this novel modeling process to improve characterization of children's hips by introducing 3-D anatomic parameters of interest. We divided our study in three steps. First, we defined three anatomic landmarks and tested their reproducibility. Second, using these points, we computed nine 3-D parameters of interest and tested their reproducibility. Third, we compared these 3-D parameters between two age groups (younger or older than 9 years), and between dancers and nondancers.

Materials and Methods

We recruited 33 children who had minor orthopaedic problems, such as mechanical low back pain without radiographic abnormality. The mean age of the patients was 11 years (range, 3–17 years). This group was divided into three subgroups: (1) 10 were nondancers younger than 9 years; (2) 13 were nondancers older than 9 years; and (3) 10 were ballet dancers older than 9 years from the National Opera of Paris. These dancers needed spine radiographs for systematic spine control, required by the National Opera of Paris medical staff, before being accepted in the National ballet school. All radiographs were obtained for medical

purposes, the child was fully informed, and the approval of both parents was required. The protocol (CPP-PRP-6001) was approved by our ethics and advisory council.

We used a biplanar x-ray system (EOS®, Biospace Med) to acquire radiographs of subjects in a standing position (Fig. 1) [7]. The 3-D geometries of the 66 hips were obtained using a specific reconstruction software based on a morphorealistic parametric subject-specific model [1, 3, 13] (Fig. 2). The software output coordinates of several anatomic regions, eg, the center of the femoral head, the points forming the acetabular edge. We then used a dedicated MATLAB® program (The Mathworks, Inc, Natick, MA, USA) to input these regions to define our three anatomic landmarks and compute the nine 3-D anatomic parameters of interest, based on the 3-D bone geometry model obtained for each patient. The three landmarks were: (1) the center (AC) of the least-square sphere fitting the acetabulum (Fig. 3A); (2) the orthogonal projection (M) of AC on the least-square plane (P) fitting the edge of the acetabulum (Fig. 3A); and (3) the center (Z) of the least-square sphere fitting the femoral head (Fig. 3B).

The nine 3-D anatomic parameters of interest were: (1) the distance (ZM) between the center of the femoral head (Z) and its projection (M) on the plane fitting the edge



Fig. 1 The patient is standing in the appropriate position in the biplanar x-ray machine.

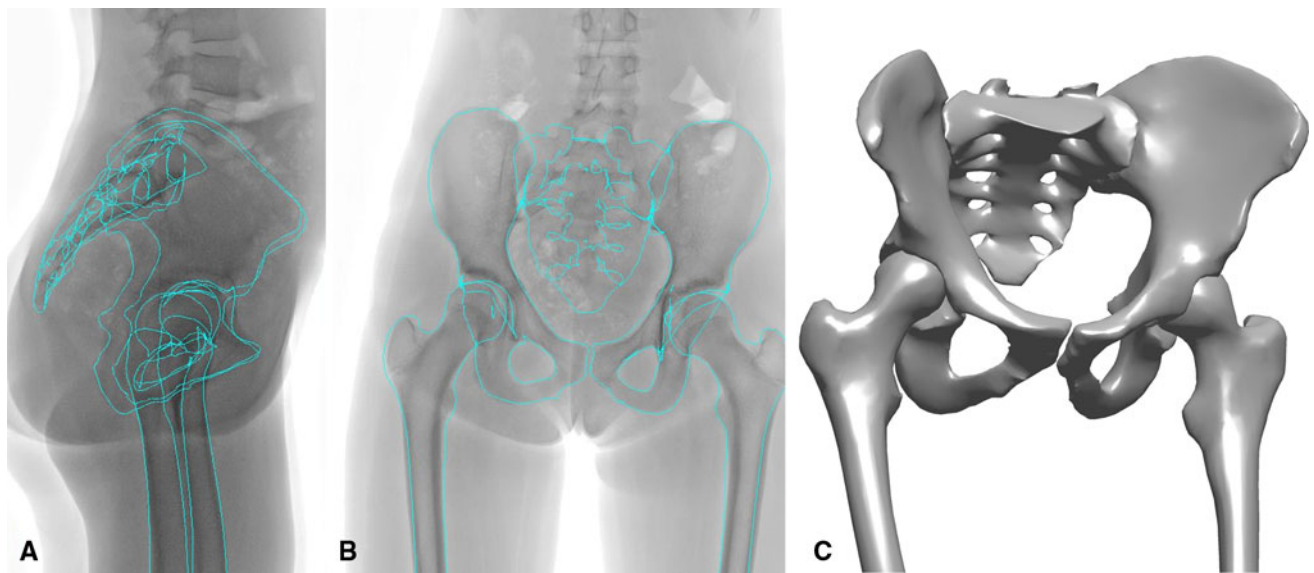
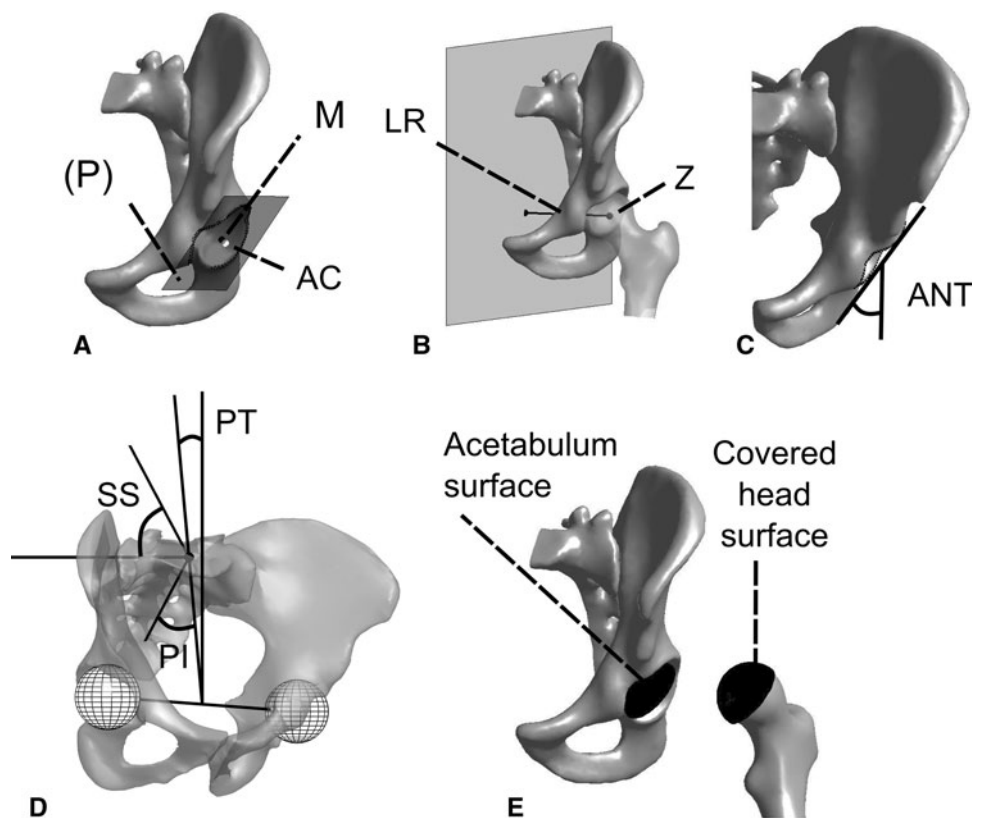


Fig. 2A–C Reconstruction of the bony structures using two biplanar x-ray images is shown. The 2-D contours on the (A) lateral and (B) frontal views are seen on these radiographs. (C) The 3-D model was obtained after manual adjustments of the contours.

Fig. 3A–E The anatomic landmarks and parameters are shown for (A) points M (the orthogonal projection of the AC), AC (the center of the least-square sphere fitting the acetabulum), and plane (P) fitting the acetabular edge; (B) the distance of the lateralization ratio (LR) between the center of the femoral head (Z) and its projection on the midplane; and (C) acetabular anteversion (ANT). (D) The three pelvic indexes, sacral slope (SS), pelvic index (PI), and pelvic tilt (PT) and (E) computation of acetabular formation and femoral head covering indexes are shown. The black points represent the acetabulum surface on the pelvis model and the zone of the head covered by the acetabulum on the femur model, respectively.



of the acetabulum, which is an index of the degree of decentralization [15]; (2) the intercenter distance (IC) between the center of the femoral head (Z) and the center of the acetabulum (AC); (3) the lateralization ratio (LR) (Fig. 3B), which is the distance between the center of the

femoral head (Z) and its orthogonal projection on the midplane of the pelvis, normalized by the radius of the sphere fitting the acetabulum; (4) acetabular anteversion (Fig. 3C), (5) pelvic tilt (PT) (Fig. 3D), (6) pelvic incidence (PI) (Fig. 3D), (7) sacral slope (SS) (Fig. 3D);

Table 1. Landmark positions and parameter reproducibility for the five groups

Group	Number of hips	95% CI (mm)					95% CI LR	95% CI (°)				95 % CI (%)	
		Z	AC	M	ZM	IC		PT	SS	PI	ANT	AF	FHC
All	264	2	3	3	4	4	1	2	3	3	6	16	13
Younger than 9 years	80	2	3	3	4	5	1	2	2	3	6	20	18
Older than 9 years	184	2	3	3	4	4	1	2	3	3	5	14	10
Nondancers	104	2	4	3	4	5	1	2	3	3	6	14	11
Dancers	80	2	2	2	2	3	1	2	3	2	5	13	9

Z = center of the femoral head; AC = center of the acetabulum; M = projection of the femoral head; ZM = ZM distance; IC = intercenter; LR = lateralization ratio; PT = pelvic tilt; SS = sacral slope; PI = pelvic incidence; ANT = anteversion; AF = acetabulum formation index; FHC = femoral head covering index.

Table 2. Values (mean and standard deviation) of the nine anatomic parameters of interest.

Group	Number of hips	Mean (mm) (SD)		Mean (SD)	Mean (°) (SD)				Mean (%) (SD)	
		ZM	IC	LR	PT	SS	PI	ANT	AF	FHC
All	66	5 (2)	4 (2)	3 (1)	7 (7)	-39 (8)	45 (9)	8 (6)	82 (9)	76 (10)
Younger than 9 years	20	6 (2)	4 (2)	3 (1)	5 (7)	-33 (9)	39 (8)	7 (6)	75 (9)	67 (9)
Older than 9 years	46	5 (2)	4 (1)	3 (1)	7 (7)	-41 (7)	48 (8)	9 (6)	85 (7)	80 (7)
Nondancers	26	5 (2)	4 (2)	3 (1)	6 (7)	-43 (7)	49 (9)	9 (6)	87 (6)	83 (7)
Dancers	20	5 (1)	4 (1)	3 (1)	8 (7)	-38 (6)	46 (6)	9 (5)	82 (8)	77 (6)

ZM = ZM distance; IC = intercenter; LR = lateralization ratio; PT = pelvic tilt; SS = sacral slope; PI = pelvic incidence; ANT = anteversion; AF = acetabulum formation index; FHC = femoral head covering index.

(8) index of formation of the acetabulum (AF), which is the ratio between the surface of the acetabulum and the surface of half the sphere fitting the acetabulum (Fig. 3D) (an AF index of 100 therefore would indicate a half-hemispheric acetabulum); and (9) the femoral head covering index (FHC), which is the ratio between the surface of the femoral head covered by the acetabulum and the surface of half the sphere fitting the femoral head (Fig. 3E).

To assess the reproducibility of our variables (anatomic landmarks and parameters), two operators (VV, VR) reconstructed two 3-D models per patient, thus giving a set of four values per variable and hip. To assess landmark position reproducibility, the mean of the four points were computed, then the distances (d_i , for $i = 1, \dots, 4$) between each of these four points and the mean were calculated. Finally, the mean distance (d_m) was calculated and the differences ($d_{fi} = d_i - d_m$, for $i = 1, \dots, 4$), were computed. We then stored the d_{fi} for each hip in a vector, thus giving 264 values (ie, four values for each of the 66 hips), and computed the 95% CI as two standard deviations of this vector. The reproducibility of each of the nine parameters was estimated using the following method: for each hip and each parameter, the mean of the four values obtained from the four models was calculated, then the differences between each of the four parameter values and this mean were evaluated and stored in a global vector. The 95% CI then was calculated as two

standard deviations of this vector. Each parameter's value was estimated for each hip by calculating the mean of the four values obtained from the four models. Mean and standard deviation values then were calculated for all children concerned. All calculations were performed for five subcohorts: all 33 children, 10 children younger than 9 years, 23 children older than 9 years, 13 nondancers, and 10 dancers (all older than 9 years). We used XLstat software (Addinsoft, Paris, France) for the statistical analyses.

Results

The three anatomic landmarks (Z, AC, and M) defined showed position reproducibility less than 4 mm (Table 1). The most reproducible point was the center of the femoral head (Z) with a 95% CI of 2 mm. There were no differences between the two age groups, however points were more reproducible for dancers than for nondancers.

Although the reproducibility of the ZM and IC distances was similar when considering all the children, these parameters tended to be more reproducible for dancers than for nondancers, but not statistically so (Table 1). The lateralization ratio had a 95% CI of 1 for all children; this value remained the same regardless of the age and activity of the child. When considering all the children, the most

reproducible angle was pelvic tilt, with a 95% CI of 2°, whereas the anteversion angle was the least reproducible, with a 95% CI of 6°. There was better reproducibility of the femoral head covering index in older ($p < 0.001$) (older than 9 years) than in younger children.

The parameters values (Table 2) showed there was a difference between the two age groups concerning the lateralization ratio ($p = 0.008$), sacral slope ($p = 0.01$), pelvic incidence ($p = 0.002$), femoral head covering index ($p < 0.0001$), and index of formation of the acetabulum ($p < 0.0001$). Comparing nondancers with dancers, the difference occurred only for the lateralization ratio ($p = 0.01$).

Discussion

As the hip is a 3-D functioning joint, it is important to evaluate 3-D parameters with the hip in its functional standing position. In this study two biplanar x-ray images were taken, using the EOS[®] system, which provides better bone definition than MRI and lower radiation exposure than CT. The goal of our study was to introduce 3-D anatomic parameters to improve characterization of children's hips. First, we defined three anatomic landmarks and verified their reproducibility; second, these landmarks were used to compute nine reproducible parameters of interest. Third, we compared these parameters between children younger and older than 9 years, and between dancers and nondancers.

We acknowledge limitations of our study. First, the radiographs were taken with the first biplanar x-ray imaging system installed in 2003. Recent improvements in image quality could lead to greater reliability. Second, although the reconstruction methods have been validated for healthy adults and are reportedly accurate [1, 3], this has not been reported for children. To fully validate this system we would need to get high-resolution CT scans of cadaveric bones of children and compare their 3-D reconstruction with the ones from our system. Third, we have no data on the length of time the dancers had been dancing. High-intensity activity can affect remodeling [14, 16], and it is possible those who had been dancing longer could have had bony alterations whereas those who had been dancing for shorter periods would have not experienced such alterations and thus have had anatomy closer to that of nondancers. However, we found only one parameter (lateralization ratio) that differed between the two.

Reproducibility in position for anatomic landmarks was better for the center of the femoral head (Z) than for the center of the sphere fitting the acetabulum (AC) and its projection on the plane fitting the acetabulum edge (M), even though a previous study [8] proposed a method based on MRI to locate the center of the femoral head, advocating the usual difficulties to identify it in young children. The

inferior point of the acetabulum also was difficult to find, especially in children younger than 10 years, as previously reported [2].

Reproducibility of pelvic parameters was good, with a 95% CI inferior to 3°, confirming the findings of Champain et al. [4]. They reported pelvic tilt had a reproducibility of 1.2°, sacral slope of 4.0°, and pelvic incidence of 3.4°. The anteversion angle was only slightly less reproducible, with a 95% CI of 5.6°. This could be because this parameter was based on the plane best fitting the acetabulum edge, which was difficult to define on the radiographs. Finally, even though we found no clear statistical evidence, we observed a tendency for better reproducibility of the parameters for the dancers, and this may be related to their increased bone mineral content in the lower limbs and femoral necks [12], making the radiographs sharper, and because all were older than 9 years. For all these parameters, values were comparable to the traditional 2-D measured ones. For the pelvic parameters (pelvic incidence, sacral slope, and pelvic tilt), the values in our series were comparable to values reported in the literature for each age group [10, 11, 18]. The lateralization ratio evaluated the position of the center of the femoral head with respect to the acetabulum. Although we found no reference value for this ratio in the literature, the reproducibility of this parameter made it reliable to use. It would be important to evaluate the evolution of this ratio in hips of patients with orthopaedic disorders to evaluate the radiographic changes of the hip and pelvis after a treatment.

The lower reproducibility of our parameters concerns the acetabular region. On traditional 2-D radiographs, the acetabular anteversion value is approximately 20° at the end of growth [5, 6, 9, 15, 17]. On 3-D CT scans, Dandachli et al. [6] measured acetabular anteversion and concluded that its normal value is approximately 17°, ranging from 1° to 31°. In the current study, the mean value was 8.3°, but as already explained, the uncertainty of this parameter is high, related to the difficulties in modeling the acetabulum edge. Although only the lateralization ratio was different between dancers and nondancers, we found that five of nine hip parameters were different between the children of the two age groups. In our series, there is an increase with age of the femoral head covering index and the index of formation of the acetabulum, matching the progressive lateral ossification of the acetabulum and of the femoral head coverage with growth. These findings suggest the proposed 3-D anatomic parameters are reproducible and therefore may be used to characterize children's hips.

Our study provides preliminary values for 3-D parameters in healthy children's hips. Three-dimensional reconstructions of the hips and pelvis of children were created from biplanar x-ray images, regardless of the child's age. Image quality improvements and modeling refinement should

decrease the uncertainty of the parameters related to the acetabulum and its edge. Modeling a cartilaginous zone could be of particular interest. For example, the triradiate cartilage is used to draw a reference line to calculate many angles on the radiographs of a child's hip. The reconstruction of these zones could be added in future studies to improve the accuracy of such 3-D models. Although most of our parameters were comparable to those in the literature, further work is needed to acquire biplanar x-ray images and CT scans, the latter remaining the gold standard for 3-D bone modeling, to obtain a direct validation. These studies will have to be performed on cadaveric specimens to avoid high radiation doses in children.

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