

High Accuracy of Pelvic Tilt Measurement Using Three-Dimensional Planning Software: A Validation Study Using Dry Bone Models

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The “CR Alignment” function was recently introduced in ZedHip[®], the hip joint module of ZedView[®], to evaluate pelvic tilt in non-supine positions via two-dimensional (2D)–3D matching using radiographs. However, its accuracy has not been validated. This study therefore evaluated the accuracy of pelvic tilt measurements using the CR Alignment function in dry pelvic bone specimens. Two cadaveric pelvic bone models were placed in nine orientations (anterior/posterior tilt and left/right rotation). Both radiographic and CT images were acquired in each position. In Study 1, pelvic tilt measured directly from CT images was defined as the “true value.” Three observers used the CR Alignment function to calculate pelvic tilt on radiographs, and measurement errors were determined relative to the true values. In Study 2, measurement errors were compared between matched (same position) and mismatched (different position) imaging. In Study 1, the mean measurement error was $1.28 \pm 0.64^\circ$. Intra- and interobserver intraclass correlation coefficients were 0.996–0.998 and 0.997, respectively. In Study 2, the mean errors were $1.20 \pm 0.88^\circ$ (matched) and $1.32 \pm 1.03^\circ$ (mismatched). This software exhibited high accuracy and reproducibility in 2D–3D matching of pelvic tilt, with lower variability under matched acquisition, demonstrating its utility for pre- and postoperative assessment in joint arthroplasty.

Key words: total hip arthroplasty, pelvic tilt, three-dimensional planning software, two-dimensional and three-dimensional matching, radiographic analysis

In recent years, three-dimensional (3D) measurement and preoperative planning software has been widely used for accurate implant placement in hip replacement surgery [1–4]. This software generally uses data reconstructed from computed tomography (CT) images taken in the supine position; however, pelvic tilt varies between supine, sitting, and standing positions, thereby altering the orientation of the placed cup [5,6]. Improper cup positioning and angulation can

lead to complications such as dislocation, wear, and limited range of motion [7–9], which may adversely affect treatment outcomes and patient satisfaction [10]. Dynamic pelvic movement has traditionally been assessed using parameters such as sacral slope measured on lateral radiographs of the spine and pelvis [11–14]. However, these measurements are affected by rotation in the coronal and axial planes, which can compromise measurement accuracy [15,16].

We routinely use ZedView[®] (LEXI Co., Tokyo), a 3D

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measurement and preoperative planning software, for both surgical planning and postoperative evaluation to achieve more accurate implant placement and determine precise cutting lines in pelvic and femoral osteotomy [13,15,17]. In a previous study using dry bone models, we reported that ZedHip[®], the hip joint module of ZedView[®], demonstrated high measurement accuracy [18].

In 2024, a new function termed “CR Alignment” was introduced in ZedHip[®] (Version 17.0.0). This function performs two-dimensional (2D)-3D matching by aligning the contour of a CT-based three-dimensional pelvic model with an anteroposterior pelvic radiograph, thereby enabling the estimation and measurement of pelvic tilt even on non-supine plain radiographs. However, no previous study has evaluated the accuracy of this method. Accordingly, in this study, we aimed to assess the accuracy of pelvic tilt measurements in dry bone models using the CR Alignment function. We hypothesized that pelvic tilt would be measured with high accuracy and that measurement accuracy would be greater when the CT and radiographic images were acquired in the same pelvic position.

Materials and Methods

Two dry bone pelvic specimens were used in this study. The specimens were discovered in a skeletal state between 1980 and 2020 and were preserved as intact pelvic rings, with the innominate bones and sacrum connected at the sacroiliac joints and pubic symphysis. The age and sex of the specimens were unknown (Fig. 1).

Data were collected for research purposes from December 24, 2024 to March 31, 2025. The authors did not have access to information that could identify the individuals from whom the specimens were obtained.

Pelvic position. The pelvic bone was arbitrarily set in the neutral position as a reference. Subsequently, nine pelvic positions were established by combining right and left axial rotation with anterior and posterior tilt, as illustrated in Fig. 2. These positions were selected because of the practical difficulty of fixing the pelvic bone at a precise angle relative to a specific plane.

The pelvic bone, aligned in each position, was fixed onto a board using a low-resilience foam pad and bandage to prevent movement (Fig. 3). Moreover, a level-

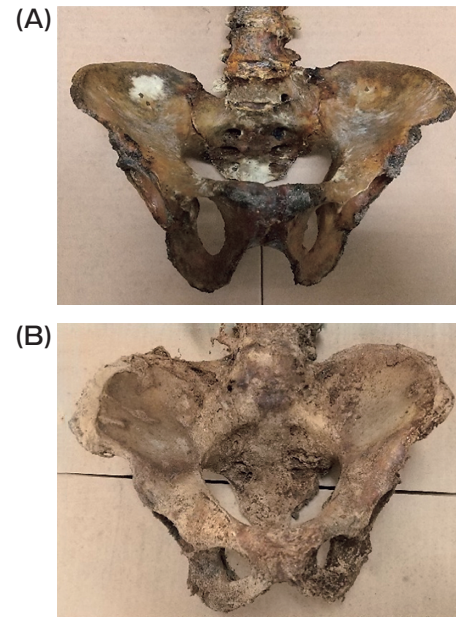


Fig. 1 Dry pelvic bones used for measurements. (A) Pelvis 1; (B) Pelvis 2.

ing device was used to ensure that the board was horizontal with respect to the ground during radiographic imaging and CT scanning (Fig. 4).

Radiological examination. As illustrated in Fig. 2, each pelvic bone was fixed in one of the nine distinct positions. For each position, one radiograph and one CT scan were acquired, resulting in nine radiographs and nine CT images per specimen. Radiographs were acquired at a source-to-image distance of 100 cm. The X-ray beam was centered vertically on the midline at the midpoint between the anterior superior iliac spine and distal femur (standard centering at the pubic symphysis). The collimation field was 17 × 17 inches, and the exposure parameters were 70-75 kV and approximately 20 mAs. CT scans were acquired at 120 kVp and 369 mAs with a 1.0-mm slice thickness and reconstructed using the FC30 kernel.

Measurement.

1. Study 1: Validation of 2D-3D Matching Accuracy Using the CR Alignment function.

To assess the accuracy of 2D-3D matching using the CR Alignment function, each paired set of radiograph and CT images was analyzed using ZedHip[®] (Fig. 5). The pelvic tilt measured directly from the CT image, defined by the functional pelvic plane (FPP), served as the reference (“true value”). The FPP was derived from

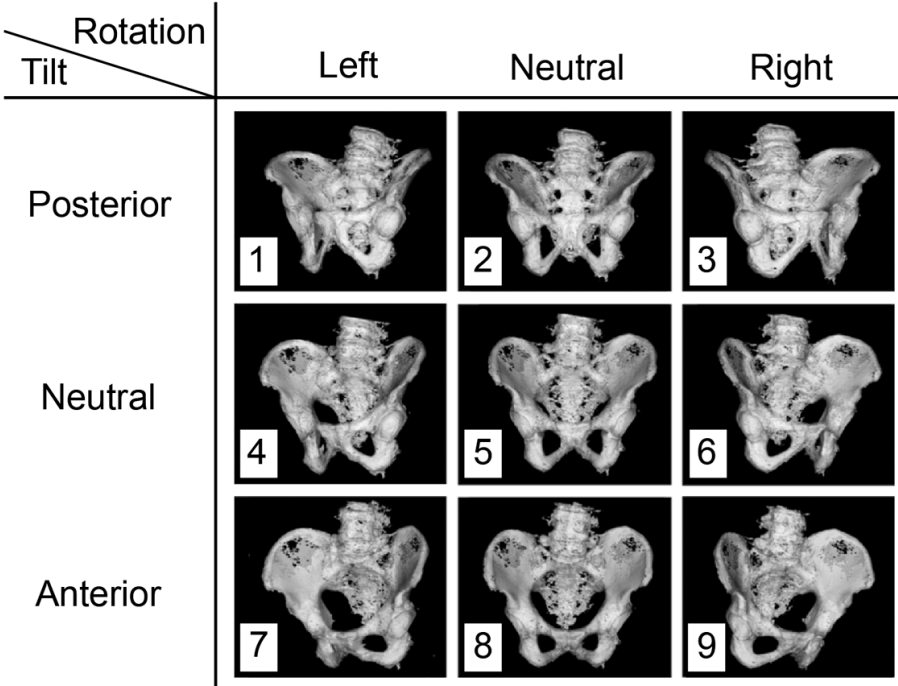


Fig. 2 Nine pelvic positions measured in this study. The pelvic bone was arbitrarily set in the neutral position as a reference, after which nine pelvic positions were established by combining right and left axial rotation with anterior and posterior tilt. Position 5 indicates the neutral/reference position.

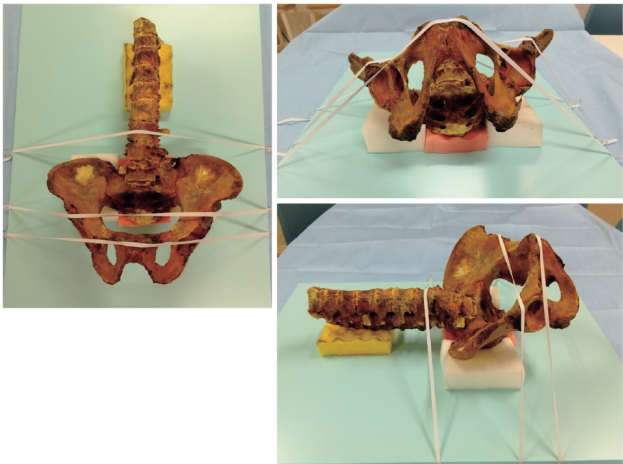


Fig. 3 Fixation of the dry pelvic bone specimens. After adjusting the pelvic tilt, a band and a low-resilience foam pad were used to hold the dry pelvic bone and prevent movement.

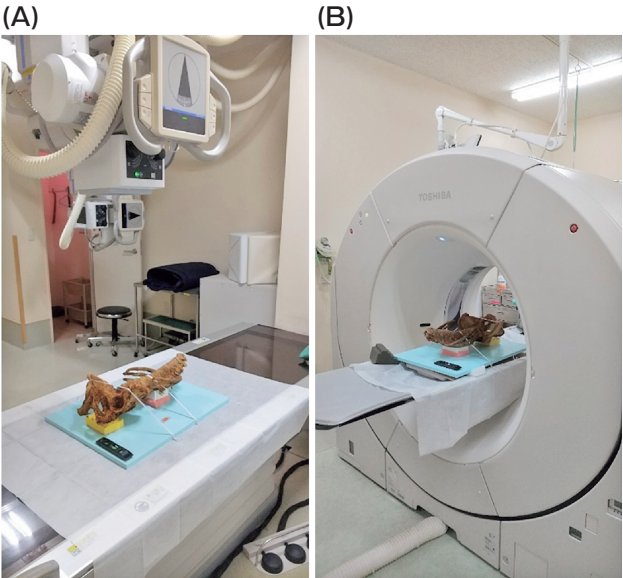


Fig. 4 Computed radiography (CR) and CT imaging of fixed pelvic bones. Dry bones were fixed to a board in nine positions and imaged using radiography (A) and CT (B). A leveling device was used to ensure that the board was level with the ground.

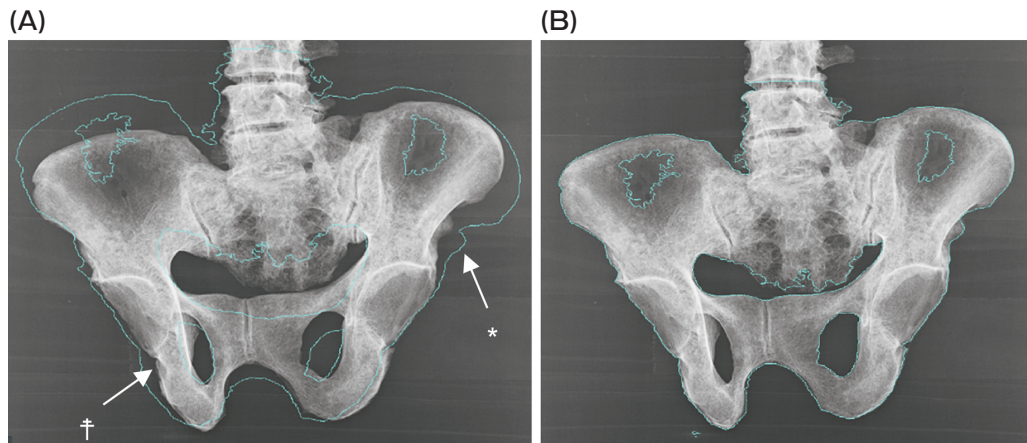


Fig. 5 2D-3D matching using the CR alignment system. **(A)** Before 2D-3D matching. **(B)** 2D-3D matching was performed by aligning the pelvic contour of the 3D image obtained from CT (blue dotted line) with the contour on the radiographic image. *contour of the 3D image obtained from CT, † contour on the radiographic image.

the anterior pelvic plane (APP), defined by the bilateral anterior superior iliac spines and pubic symphysis, and corrected solely for sagittal pelvic tilt in the supine position. The FPP was expressed as positive for anterior tilt and negative for posterior tilt relative to an APP of 0°. To ensure consistency and reproducibility, the same three radiographs were used for each CT-based pelvic model across all three observers and trials. For each of the nine predefined pelvic positions, three radiographs were systematically selected per model: one matched the same pelvic position as the CT image (“matched” condition), while the other two were deliberately selected from different positions (“mismatched” conditions). The mismatched radiographs were selected based on a predefined scheme: one differed in tilt direction (anterior vs. posterior) and the other in rotation direction (left vs. right), ensuring consistent and reproducible conditions across specimens and observers (Table 1). The measurement error was defined as the absolute difference between the reference pelvic tilt and the value obtained through 2D–3D matching, regardless of the direction of deviation.

2. Study 2: Effect of Pelvic Positional Consistency on the Accuracy of 2D–3D Matching.

The accuracy of 2D–3D matching may be adversely affected when the CT model and radiograph are acquired in different pelvic positions. In this study, the datasets from Study 1 were classified into two groups based on pelvic position: one in which the CT model and radiograph shared the same pelvic position

Table 1 Correspondence Table between 2D-3D matched CT models and radiographs

CT 3D model	CR images		
	①	②	③
1	1	5	9
2	2	6	7
3	3	4	8
4	4	8	3
5	5	9	1
6	6	7	2
7	7	2	6
8	8	3	4
9	9	1	5

One radiograph was matched to a CT model with the same identification number, corresponding to the same pelvic position, whereas the other two radiographs represented different pelvic positions. CT, computed tomography; CR, computed radiography.

(matched condition) and another in which they differed (mismatched condition). Measurement errors in pelvic tilt were evaluated separately for each group.

Registration and 2D–3D matching. Three orthopedic surgeons (observers A, B, and C), all experienced ZedView® users, independently performed the 2D–3D matching procedures. Before the main experiment, a training session using pilot radiographs and CT models (not included in the analysis) was conducted to standardize the registration procedure. This familiarization allowed the observers to practice aligning pelvic

contours and to calibrate their use of the software interface. In the CR Alignment function of ZedView[®], the contour of a three-dimensional pelvic model reconstructed from CT data is projected onto the plane of a radiographic image. The observer manually adjusts the position and orientation of the 3D model to match the pelvic radiograph. This process involves alignment of anatomical landmarks, including the iliac crest, obturator foramen, and pelvic brim. Once optimal matching is achieved, the software calculates pelvic tilt based on the spatial orientation of the FPP relative to the imaging plane. This method enables estimation of pelvic tilt from a single anteroposterior radiograph without requiring biplanar imaging or additional equipment. Each observer completed three repeated sessions at intervals of at least one week to minimize carryover or recall effects.

Statistical analysis. We used IBM SPSS Statistics for Windows (version 24.0; IBM Corp., Armonk, NY, USA) to analyze the data. Repeated-measures data were analyzed using a linear mixed-effects model (LMM) to account for the hierarchical structure of the dataset. The fixed effects included the acquisition condition (matched vs. mismatched). Random intercepts were specified for the specimens and positions, allowing for within-specimen and within-position correlations. The parameters were estimated using restricted maximum likelihood. We report fixed-effect estimates with standard errors, 95% confidence intervals, and *p*-values (*p* < 0.05 was considered statistically significant), as well as variance components and their proportions of total variance. Consistency of measurements from the surgical planning software was evaluated using intraclass correlation coefficients (ICCs) for both intra- and interobserver comparisons. ICCs were calculated using single-measure models with absolute agreement. For intraobserver reliability, a two-way mixed-effects model was used, considering the observer as a fixed effect. For interobserver reliability, a two-way random-effects model was applied, treating observers as random effects.

Ethics approval. This study was designed in accordance with the principles of the Declaration of Helsinki and approved by the Institutional Review Board of Niigata University (Approval No. 2024-0208; initial approval: December 24, 2024; extension approval: January 13, 2026). The need for informed consent was waived because this was a retrospective cross-sectional study evaluating three-dimensional measurements and

preoperative planning software; therefore, no interventions were performed.

Results

Study 1. Table 2 presents the FPP measured by the three observers and the corresponding mean value, which we defined as the true value because averaging across raters reduces individual measurement variability and provides a more robust reference standard.

The average error between the true values and the FPP measured by 2D-3D matching was 1.28°, with a maximum error of 4.9° (Table 3). The reliability of the test values was high, with mean intraobserver ICC values of 0.996–0.998 and an interobserver ICC value of 0.997 (Table 3).

Study 2. When the CT model and radiograph were acquired in the same pelvic position, the mean measurement error was $1.20 \pm 0.88^\circ$. In the LMM, mismatched conditions were associated with a +0.12° higher absolute error than matched conditions, although this difference did not reach statistical significance (estimate 0.12°, 95% CI –0.002 to 0.254, *p* = 0.054). The variance components were 0.241 for the specimen, 0.405 for the position, and 0.463 for the residual error, corresponding to ~20%, ~34%, and ~46% of the total variance, respectively. These findings indicate that measurement variability was more strongly influenced by acquisition position than by specimen-level differences.

Discussion

ZedView[®], surgical planning software developed by LEXI Co., enables 3D reconstruction, visualization, and measurement from sequential 2D CT slice images and is widely used in clinical practice, particularly in Japan. The ZedView[®] platform offers a range of specialized modules tailored to specific clinical purposes, including ZedHip[®], ZedKnee[®], ZedShoulder[®], ZedSpine[®], JIGEN[®], ZedOsteotomy[®], ZedTrauma[®], ZedView2.5D[®], ZedEdit[®], and ZedMotion[®]. Although prior studies have examined the accuracy of the software using model bones and animal specimens [19–21], our group was the first, in 2023, to demonstrate its high accuracy using human dry bone specimens [18]. Although the “CR Alignment” function was newly introduced in ZedHip[®] in 2024, no prior studies have

Table 2 Measured FPP values and corresponding “True Values” in this study

Pelvis	Position	Observer A	Observer B	Observer C	All (true value)
1	1	-39.15 ± 0.18	-39.57 ± 0.62	-39.47 ± 0.18	-39.40 ± 0.42
	2	-39.78 ± 0.32	-40.19 ± 1.15	-39.79 ± 0.12	-39.92 ± 0.72
	3	-40.46 ± 0.38	-39.67 ± 0.30	-40.62 ± 0.08	-40.25 ± 0.50
	4	-36.34 ± 0.20	-36.35 ± 1.09	-36.24 ± 0.00	-36.31 ± 0.64
	5	-36.32 ± 0.09	-36.41 ± 0.62	-36.29 ± 0.03	-36.34 ± 0.37
	6	-36.55 ± 0.13	-35.83 ± 0.15	-36.74 ± 0.06	-36.37 ± 0.41
	7	-32.06 ± 0.11	-31.68 ± 0.41	-32.14 ± 0.10	-31.96 ± 0.32
	8	-32.62 ± 0.13	-32.65 ± 1.19	-32.66 ± 0.03	-32.64 ± 0.69
	9	-33.30 ± 0.09	-33.59 ± 0.51	-33.30 ± 0.06	-33.40 ± 0.33
2	1	-12.95 ± 0.22	-12.41 ± 1.10	-12.94 ± 0.22	-12.77 ± 0.71
	2	-12.81 ± 0.18	-14.39 ± 0.98	-13.08 ± 0.08	-13.43 ± 0.90
	3	-12.70 ± 0.43	-11.76 ± 0.57	-13.16 ± 0.12	-12.54 ± 0.72
	4	-9.52 ± 0.21	-11.43 ± 0.32	-9.85 ± 0.27	-10.27 ± 0.87
	5	-9.47 ± 0.16	-9.36 ± 1.01	-9.77 ± 0.16	-9.53 ± 0.62
	6	-9.07 ± 0.07	-8.62 ± 0.33	-8.77 ± 0.13	-8.82 ± 0.28
	7	1.53 ± 0.53	0.18 ± 1.11	1.12 ± 0.12	0.94 ± 0.91
	8	-2.26 ± 0.20	-3.20 ± 0.46	-2.56 ± 0.02	-2.67 ± 0.49
	9	0.14 ± 0.32	-0.04 ± 1.00	-0.01 ± 0.01	0.03 ± 0.61

Unit: degrees, *: mean ± standard deviation

The average values across the three observers were defined as the “true value” in this study.

Table 3 Measurement errors in 2D-3D matching for all observers and each observer

	Observer A	Observer B	Observer C	All
Measurement error of pelvis 1* (range) (°)	0.89 ± 0.51 (0.00–3.61)	0.89 ± 0.48 (0.00–3.39)	0.91 ± 0.41 (0.02–3.55)	0.90 ± 0.50 (0.00–3.61)
Measurement error of pelvis 2* (range) (°)	1.73 ± 0.79 (0.01–4.90)	1.57 ± 0.76 (0.04–4.41)	1.68 ± 0.68 (0.00–4.65)	1.66 ± 0.78 (0.00–4.90)
Total measurement error* (range) (°)	1.31 ± 0.65 (0.00–4.90)	1.23 ± 0.62 (0.00–4.41)	1.29 ± 0.54 (0.00–4.65)	1.28 ± 0.64 (0.00–4.90)
ICC of total measurement (95% CI)	0.997 [†] (0.996–0.998)	0.996 [†] (0.993–0.997)	0.998 [†] (0.996–0.999)	0.997 [†] (0.996–0.998)

*, mean ± standard deviation; ICC, intraclass correlation coefficient; CI, confidence interval. [†], $p < 0.001$.

assessed its accuracy. To our knowledge, this study is the first to validate this feature.

In Study 1, the mean measurement error between the true FPP values, as defined in this study, and those obtained through 2D-3D matching was 1.28°. The ICCs for both intra- and interobserver reliability ranged from 0.996 to 0.998. Although reports on 2D-3D matching based on the pelvis remain limited, previous studies have demonstrated ICCs ranging from 0.90 to 0.99 for intraobserver reliability and from 0.87 to 0.96 for interobserver reliability [22,23]. These findings are comparable to those observed in this study. Furthermore, previous studies have reported angular measurement

errors of 1–2° using ZedView[®], with ICCs ranging from 0.97 to 0.99 for intraobserver reliability and from 0.92 to 0.99 for interobserver reliability [13,24,25]. Comparable levels of accuracy have also been observed with other devices [13,26,27], supporting the validity of these findings and suggesting that the measurement precision is sufficient for clinical applications. Although the ICCs were sufficiently high in this study, even greater measurement accuracy may be achieved by integrating multiple trials from a single observer or, if possible, by combining the results from multiple observers.

However, from a clinical perspective, even small errors in pelvic tilt measurement may influence the

interpretation of functional cup orientation. Previous studies have shown that a 1° change in pelvic tilt translates into an approximately 0.7° - 1° change in functional anteversion or inclination [28-32]. Therefore, an error of 1° - 2° is unlikely to have a major effect on clinical outcomes because it remains within the generally accepted safe zone for cup placement [33-39], although the universality of this “safe zone” has been questioned [40,41]. An error of approximately 3° could become critical in borderline cases with limited spinopelvic mobility or cup positions near the edges of the safe zone [41-43]. Larger errors of 4° - 5° may produce clinically relevant deviations in functional anteversion and inclination, potentially reducing the impingement-free range of motion and increasing dislocation risk [8,44,45]. These considerations highlight the importance of minimizing pelvic tilt measurement error to ensure accurate preoperative planning and reliable postoperative risk assessment [8,28-31,41,42,44].

In our previous studies, we demonstrated the clinical utility of other 2D-3D matching software systems, such as Hip CAS[®] and Knee CAS[®] [46,47]. These systems perform 2D-3D matching using anteroposterior and 60° oblique radiographs, aligning the femoral and tibial bones or total knee arthroplasty components with CT-reconstructed 3D models. Although the accuracy of pelvic tilt assessment with these systems has not been reported, their use of biplanar radiographs may provide greater accuracy than methods relying solely on anteroposterior views [48,49]. In contrast, the CR Alignment function evaluated here requires only a single anteroposterior radiograph. Unlike conventional methods that require biplanar radiographs or additional imaging systems, it achieved high measurement accuracy without specialized imaging equipment, providing a practical and accessible solution for evaluating pelvic tilt in routine clinical settings. However, the maximum measurement error observed was 4.9° (Table 3), which may reflect the inherent limitations of single-view matching. Future studies should investigate alternative imaging strategies, such as biplanar radiography, EOS imaging, or other low-dose stereoradiographic systems, which can provide additional angular information and reduce errors related to out-of-plane pelvic rotations or poor landmark visibility [50]. Direct comparisons between single-view CR Alignment and multi-view methods are needed to clarify their relative clinical utility [51].

In Study 2, the pelvic models were categorized based

on whether the CT and radiographic images corresponded to the same pelvic position. The mixed-effects analysis showed that mismatched conditions tended to increase the error magnitude, although the effect size was small ($+0.12^\circ$) and did not reach conventional statistical significance. Variance decomposition indicated that the acquisition position accounted for more than one-third of the total variability in the FPP error. Because, in clinical use, the CR Alignment function matches a 3D pelvic model reconstructed from supine CT with radiographs obtained in standing or sitting positions, some discrepancies are inevitable. Based on these findings, careful positioning of the pelvis to face forward and minimizing rotational differences during CT and radiograph acquisition may help reduce measurement variability [52]. Therefore, standardizing pelvic orientation during imaging could minimize error variability and enhance the reliability of pelvic tilt assessment using the CR Alignment function.

The results of this study suggest that the CR Alignment function can be applied across various postural conditions, including supine, standing, and sitting, and can provide accurate and reproducible measurements for assessing pelvic tilt. Another noteworthy aspect is that the CR Alignment function allowed us to evaluate pelvic orientation in the transverse plane, which cannot be directly visualized on conventional radiographs. These features highlight the novelty of the method and underscore its potential clinical utility in assessing three-dimensional pelvic orientation. If range-of-motion simulation becomes feasible using pelvic tilt data obtained from this software, it may enable a more comprehensive evaluation of dislocation risk across various postural and limb positions.

This study had some limitations. First, only two dry human pelvises with an intact pelvic ring were available for analysis because pelvic bones, particularly the innominate bones, are prone to environmental or animal-related damage [53-55]. These specimens lacked soft tissues or implants, and their sex and age were unknown. Therefore, morphological diversity across populations could not be assessed. Although each specimen was tested in nine different orientations, which increased the number of positional conditions and partially compensated for the limited sample size, the restricted number and type of specimens inevitably limited the generalizability of the findings. Furthermore, because this study was designed as an initial validation

study using a small number of specimens, thresholds for mean absolute error and ICC were not predefined, which may further limit the interpretation of the results. Future studies involving larger numbers of specimens and clinical imaging datasets are required to confirm the reproducibility, applicability, and robustness of the CR Alignment function in real-world surgical practice.

Second, although the dry bone specimens were fixed to a board and aligned parallel to the ground using a leveling device for both radiographic and CT acquisition, minor deviations in positioning cannot be completely ruled out. However, in clinical practice, pelvic tilt may vary even when images are acquired in the same position, and this variation cannot be verified retrospectively. Moreover, the use of actual human bones, rather than artificial bone models, reduced potential model-related biases and should be considered a strength of this study.

Third, the true FPP was defined as the mean of three independent CT measurements. Although averaging across raters reduces random variability and is more robust than a single observer's measurement, it cannot eliminate observer error. The averaged reference value may therefore have introduced bias into the estimated accuracy of the CR Alignment function. Future studies should consider repeated measurements by a designated reference rater or a consensus reading to minimize this potential bias.

Fourth, observer training and bias must be considered. Although we attempted to minimize variability by providing structured training and spacing of repeated sessions, the study design did not permit blinding of the pelvic orientation or complete randomization of the test order. Consequently, the possibility of observer learning effects or unintentional bias cannot be ruled out.

Finally, the vendor's internal registration algorithm is proprietary; thus, numerical optimization details and stopping tolerances are not disclosed. Therefore, we relied on a pragmatic visual convergence check and repeated measurements to assess reproducibility, and we did not perform a formal robustness or failure-mode analysis. Potential failure modes include substantial mismatch between CT and radiographic pelvic orientation; poor edge contrast or pelvic overlap with bowel/gonadal shadows; and inaccuracies in radiographic geometry metadata.

Future research should also extend the application of this method to the assessment of hip torsion, particu-

larly the evaluation of cervicofemoral anteversion. Because femoral anteversion plays a critical role in hip biomechanics, stability, and implant positioning, integrating this parameter with pelvic tilt assessment could provide a more comprehensive understanding of three-dimensional hip alignment. Such investigations will require whole cadaveric specimens or clinical imaging datasets that include both the pelvis and femur.

In conclusion, the CR Alignment function demonstrated high accuracy and reproducibility in 2D-3D matching. Measurement variability was lower when CT and radiographic images were acquired in the same pelvic position. Care should therefore be taken to reduce rotational mismatch at the time of image acquisition to further enhance reliability in routine practice. These findings suggest that the method can be applied under supine, standing, and sitting conditions, although further validation in clinical settings is warranted.

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