

RESEARCH ARTICLE

Reliability and Validity Analysis of Pelvic Sagittal Inclination Calculated by Inverse Cosine Function Method on Pelvic Anteroposterior Radiographs

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Objective: Evaluation of sagittal pelvic tilt is significant for hip surgeons. However, the accurate measurement of pelvic sagittal inclination (PSI) is still a challenge. The objective of this study is to propose a new method for measurement of PSI from pelvic anteroposterior radiograph based on the inverse cosine function obtained from individualized pelvic model.

Methods: Collecting the imaging data of 30 patients with both pelvic CT and full-length spine radiographs. Establishing pelvic model by customized 3D reconstruction software. The length of three groups of longitudinal and transverse line segments ($A'p$ and B') were measured from full-length spine anteroposterior radiographs. The corresponding anatomical parameters, including A , B , b , $\angle\alpha$, $\angle\gamma$, were measured and calculated on the same patient's pelvic model. The estimated PSI (ePSI) based on three groups of anatomical landmarks, including ePSI-1, ePSI-2, and ePSI-3, were calculated by equation, $ePSI = \arccos\left(\frac{A'p}{|b^*B'|}\right) - \angle\alpha$, and compared with the actual PSI (aPSI) measured by Surgamap software. For the reliability and validation evaluation, three observers measured these parameters in two rounds. Intra-class correlation and inter-class correlation were both calculated. Bland-Altman method was used to evaluate the consistency between the estimated PSI (ePSI) and the actual PSI (aPSI).

Results: ePSI-1 and ePSI-2 showed excellent intra-observer reliability (0.921–0.997, $p < 0.001$) and inter-observer reliability (0.801–0.977, $p < 0.001$). ePSI-3 had a fair inter-observer reliability (0.239–0.823, $p < 0.001$). ePSI-1 showed the strongest correlation with aPSI ($r = 0.917$, $p < 0.001$). Mean (maximum) absolute difference of ePSI-1, ePSI-2, and ePSI-3 is 2.62° (7.42°), 4.23° (13.78°), and 7.74° (31.47°), respectively. The proportion of cases with absolute difference less than 5° in three groups were 86.7% (ePSI-1), 66.7% (ePSI-2), 56.7% (ePSI-3).

Conclusion: This new method based on inverse cosine function has good reliability and validity when used in the evaluation of PSI on pelvic anteroposterior radiographs.

Key words: Anteroposterior radiograph; Computed tomography; Pelvic sagittal inclination; Total hip arthroplasty

Introduction

Pelvic sagittal inclination (PSI) is a sagittal parameter defined as the angle between the anterior pelvic plane (APP) and a standard vertical line. As a functional parameter, the PSI is vital in assessing pelvic functional position in patients undergoing total hip arthroplasty (THA) and in

guiding the intraoperative orientation of the acetabular component¹. Numerous studies have shown that changes in PSI can also directly affect the anteversion and inclination of the acetabular component, which further leads to increased risks of implant impingement and dislocation after THA^{2,3}. Previous research described a “safe zone” of acetabular inclination

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($40^\circ \pm 10^\circ$) and anteversion ($15^\circ \pm 10^\circ$)⁴, but several authors have found that the safe zone is not safe due to dynamic changes in pelvic position^{5,6}. A few studies have shown that a 5° change in pelvic tilt corresponds to a 4° change in anteversion and a 1.5° change in inclination^{7,8}. Changes $>5^\circ$ in acetabular positioning have been deemed clinically meaningful. Alignment of the pelvic functional position should be carefully analyzed before THA to avoid excessive wear of the prosthesis, implant failure, and dislocation. Therefore, it is of great significance to conveniently and accurately estimate PSI.

In theory, the PSI should be measured using lateral pelvic radiographs. However, lateral radiographs of the pelvis are not routinely performed in patients with hip joint disease. Anatomical landmarks, including the anterior superior iliac spine (ASIS) and femoral head, are not always well visualized on lateral pelvic radiographs due to poor contrast or the presence of intestinal gas⁹. Although some researchers suggest that both standing and sitting lateral radiographs are necessary for patients with hip joint disease, pelvic anteroposterior (AP) radiographs are still the main method used to evaluate the pelvis in outpatient services and hip surgery.

In contrast to lateral radiographs, AP pelvic radiographs and computed tomography (CT), with clear anatomical landmarks, are the commonly used imaging modalities. Therefore, many researchers have started to estimate PSI using a 2D–3D matching technique to match AP radiographs of the pelvis with the three-dimensional CT model^{10,11}. However, the accuracy of such methods remains questionable. In recent years, some researchers have found strong correlations between PSI and numerous parameters measured from AP pelvic radiographs, including the height and width of the obturator foramina, sacro-femoral-pubic angle, pelvic foramen aspect ratio, distance between the pubic symphysis and a line connecting the femoral head centers, and so on^{12–15}. There has also been an attempt to predict a patient's PSI using regression equations. Although the correlation coefficient of the regression equations obtained

from the research sample is excellent, the authors still do not recommend using these regression equations to predict the sagittal rotation of the pelvis in clinical practice, because it is easy to produce large errors ($>10^\circ$)¹⁴.

In this study, two methods were used for the measurement and calculation of the individual PSI based on imaging data collected from 30 patients. The objectives of the current study were (i) to propose a new method to estimate the PSI of a specific individual through the inverse cosine function between the parameters measured from pelvic AP radiographs and CT models, (ii) to analyze the reliability and validity of this novel estimation method, and (iii) to discuss the advantages and disadvantages of this novel method.

Materials and Methods

Patients

We searched our image database for patients who underwent both full-length spine radiography and pelvic CT. The inclusion criteria were as follows: (i) age between 20 and 80 years; (ii) full-length spine radiographs with both AP and lateral radiographs, and complete pelvic images including the sacrum, ASIS, pubic symphysis, and femoral head; and (iii) CT scan showing no obvious fracture, surgery, or deformity of the pelvis. Patients with severe pelvic osteoporosis or degeneration that affected identification of anatomical landmarks were excluded. Full-length spine radiographs were obtained in the standing position. Thirty patients were selected for this study. Pelvic CT images were acquired with the pelvis in a neutral position and the lower limbs naturally straight at a slice thickness of 0.625 mm. This study was approved by the institutional review board of our hospital (SH9H-2019-T80-2).

Reconstruction of the Pelvic Model

The reconstruction of the 3D pelvic model is shown in Figure 1. CT images of the patients were saved in the DICOM format and imported into the SPINEPARA software developed by our engineers. The 3D pelvic surface mesh

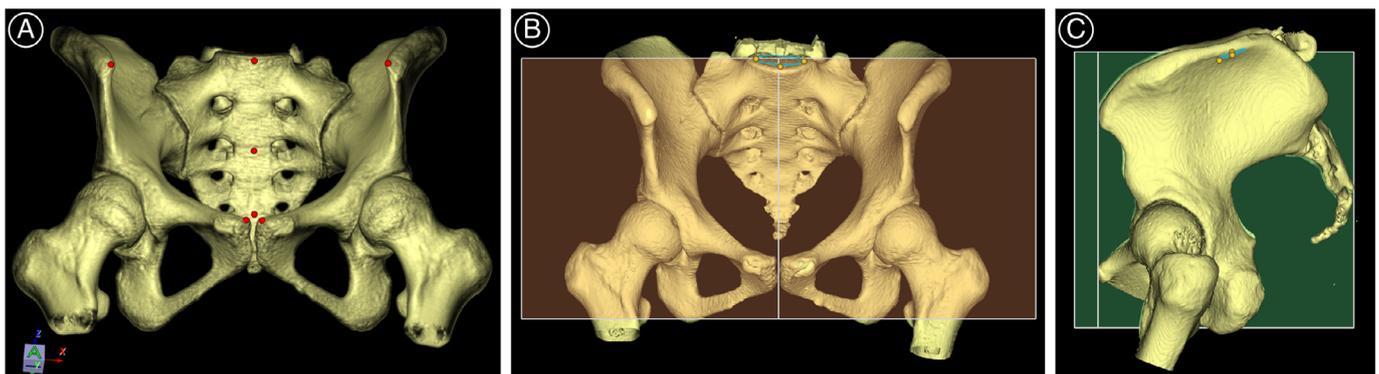


FIGURE 1 Reconstruction of 3D pelvic model. (A) Anatomical landmarks were manually selected to determine the anterior pelvic plane (APP) and the mid-sagittal plane (MSP). (B) Determination of the sacral endplate on the coronal view. (C) Sagittal view of the pelvic model

models, including the hip joint, were reconstructed according to the protocol of a previous study¹⁶. The pelvis was positioned according to the APP proposed by Lewinnek *et al.*⁴ and the midsagittal plane (MSP). To determine the APP perpendicular to the horizontal plane, four bony landmarks in the pelvic model were manually selected: bilateral pubic tubercles and ASISs. The midpoint of the pubic tubercles, representing the superior margin of the pubic symphysis, was automatically determined using a unique iterative algorithm. Three markers were selected along the anterior median line of the sacrum to determine the MSP. The iterative closest point algorithm was used to make the MSP perpendicular to APP. The range of the sacral endplate was selected using an ellipse tool, and surface points within the ellipse range were extracted and projected onto the MSP. The midpoint of the sacral endplate was calculated automatically. Capital letters C and D represent the midpoints of the

sacral endplate and the superior margin of the pubic symphysis, respectively.

To ensure the consistency of each model, the standard position for the selection of anatomical landmarks of the pelvic model should meet the following requirements: (1) the anterior median line of the sacrum overlaps the median line of the pubic symphysis, (2) the superior edge of the pubic superioris is tangent to the lower edge of the fourth anterior sacral foramen, and (3) the lower edge of the bilateral ischia is tangent to the horizontal line. The ASIS marker is the most medial point of the anterior iliac crest. The most medial point of the superior edge of the superior pubis represents the landmark point of the pubic tubercles.

Parameter Measurement in the Pelvic Model

The parameter measurements in both the pelvic model and AP radiography are shown in Figure 2. Two fitting spheres

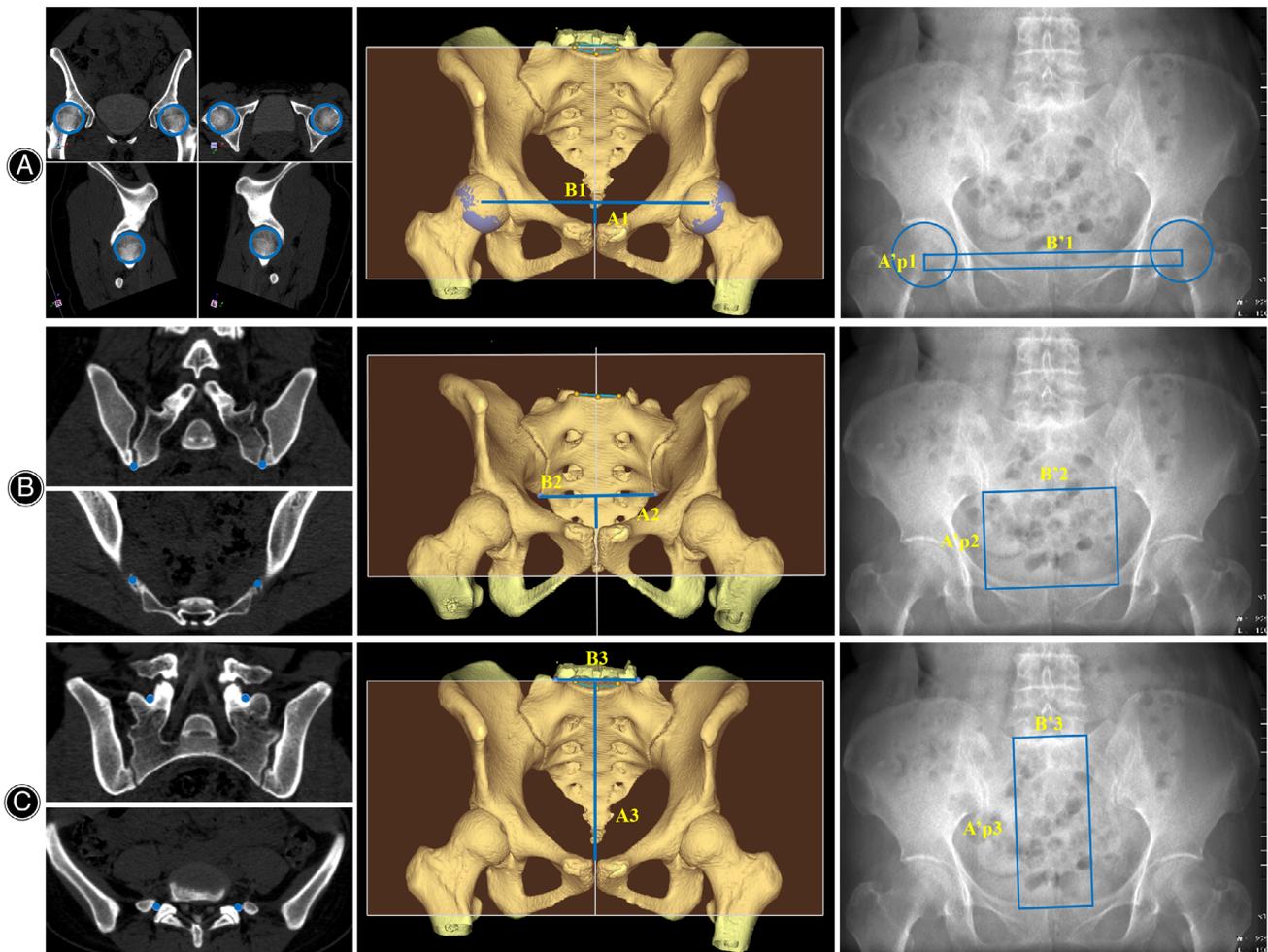


FIGURE 2 Fitting and measurement of three groups of anatomical landmarks. (A) Fitting of bilateral femoral heads on coronal, sagittal, and cross-sectional planes, and the measurement of related parameters. (B) Fitting of the lowest point of the inferior margin of sacroiliac joint (IMSJ) on coronal and cross-sectional planes, and the measurement of related parameters. (C) Fitting of the junction of iliac wing and superior articular process of S1 (JIS1) on coronal and cross-sectional planes, and the measurement of related parameters

TABLE 1 Parameters measured from both pelvic model and full-length spine radiographs

Parameters measured from pelvic model	
A	The vertical distance from superior margin of pubic symphysis (D) to the line connecting the centers of the two spheres represented the bilateral femoral heads (A1), the lowest point of the inferior margin of sacroiliac joint (IMSJ) (A2), as well as the junction of iliac wing and superior articular process of S1 (JIS1) (A3)
B	B1: the distance between the centers of the two fitting spheres that match the femoral heads B2: the distance between the centers of the two fitting spheres that represent the IMSJ B3: the distance between the centers of the two fitting spheres that represent the JIS1
$\angle\alpha$	$\angle\alpha 1$: the angle between the line connecting the midpoint (O1) of the line connecting bilateral femoral heads and superior margin of pubic symphysis (D) and the anterior pelvic plane (APP) $\angle\alpha 2$: the angle between the line connecting the midpoint (O2) of the line connecting bilateral IMSJ and D and APP $\angle\alpha 3$: the angle between the line connecting the midpoint (O3) of the line connecting bilateral JIS1 and D and APP
$\angle\gamma$	The angle between the line connecting the midpoint of the line connecting bilateral femoral heads (O1) and the midpoint of the sacral endplate (C) and APP
Parameters measured from full-length spine anteroposterior radiographs	
A'p	The vertical distance from superior margin of pubic symphysis (D) to the line connecting the centers of the bilateral femoral heads (A'p1), IMSJ (A'p2), as well as JIS1 (A'p3)
B'	B'1: the distance between the centers of the femoral heads B'2: the distance between the centers of the IMSJ B'3: the distance between the centers of the JIS1
Parameters measured from full-length spine lateral radiographs	
PT	Angle between the line joining the center of the S1 endplate and the midpoint of the hip axis and the vertical line in standing position

were used to match the femoral heads with the maximal diameter in the coronal, sagittal, and cross-sectional planes (Figure 2(A)). Furthermore, the diameter of other fitting spheres was reduced to 1 mm to fit the lowest point of the inferior margin of the sacroiliac joint (IMSJ) and the junction of the iliac wing and superior articular process of S1 (JIS1) on the coronal and cross-sectional planes (Figure 2(B,C)). The IMSJ was determined on a section of the lowest layer containing the anatomical structure. The midpoint of the line connecting both femoral heads, IMSJ, and JIS1 are represented by O1, O2, and O3, respectively.

Three groups of parameters, including A, B, $\angle\alpha$, and $\angle\gamma$, were measured from each pelvic model (Table 1). A represents the vertical distance from D to the line connecting the centers of the two spheres representing the femoral heads (A1), IMSJ (A2), and JIS1 (A3). B refers to the distance between the centers of the two fitting spheres that match the femoral heads (B1), IMSJ (B2), and JIS1 (B3). $\angle\alpha$, including $\angle\alpha 1$, $\angle\alpha 2$, and $\angle\alpha 3$, represents the angle between the line connecting O1/O2/O3 and D and APP. $\angle\gamma$ is the angle between the line connecting O1 and the midpoint of the sacral endplate (C) and APP.

Parameter Measurement in the Full-Length Spine Radiographs

From the full-length spine AP radiographs, A'p and B', projection distances of A and B were measured using the rectangular box and concentric circle tools of Microsoft PowerPoint 2016 (Figure 2). Full-length spine lateral radiographs were imported to Surgimap for Windows (Version 2.3.2.1) to survey the value of the pelvic tilt (PT)¹⁷, which is defined as the angle between the line joining the center of the S1 endplate and the midpoint of the hip axis and the vertical line in the standing position. Radiological measurements were performed twice independently by three examiners in all 30 patients, with an interval of 2 weeks.

Calculation of PSI

The standing X-ray image of the pelvis can be regarded as a projection of a three-dimensional model onto a two-dimensional plane. The principle of the PSI calculation formula is illustrated in Figure 3.

For the pelvis of a specific individual, $\angle\alpha$, A, and B are fixed anatomical parameters that are measured directly from the 3D pelvic model. The ratio of A to B is also a fixed value ($b = A/B$). On a standard standing pelvic radiograph, A' is defined as the projection distance of A on the lateral radiograph, and B' refers to the projection distance of B on the AP radiograph. Because the line segments of A and B are parallel to the sagittal and coronal planes, respectively, A' and B' also satisfy the equation $b = A'/B'$.

When APP is perpendicular to the horizontal plane ($\text{PSI} = 0^\circ$), parameters such as A', A'p, and $\angle\alpha$, measured from digitally reconstructed lateral radiographs, satisfy equation (1) (Figure 3(A)). In this case, $\angle\gamma$ is equal to PT (Figure 3(B)).

$$\cos(\alpha) = \frac{A'p}{A'} \quad (1)$$

$$PT = \gamma \quad (2)$$

When the angle between APP and the vertical line is β ($\text{PSI} = \beta$), the relationship between A', A'p, and $\angle\alpha$, can be expressed by equation (3). At this point, PT is equal to the sum of γ and β (Figure 3(C)).

$$\cos(\alpha + \beta) = A'p/A' \quad (3)$$

$$PT = \gamma + \beta \quad (4)$$

Unfortunately, A' cannot be measured from AP radiographs; that is only possible for B' and A'p. Therefore, the fixed equality relation $b \cdot B' = A'$ is used to replace A' in

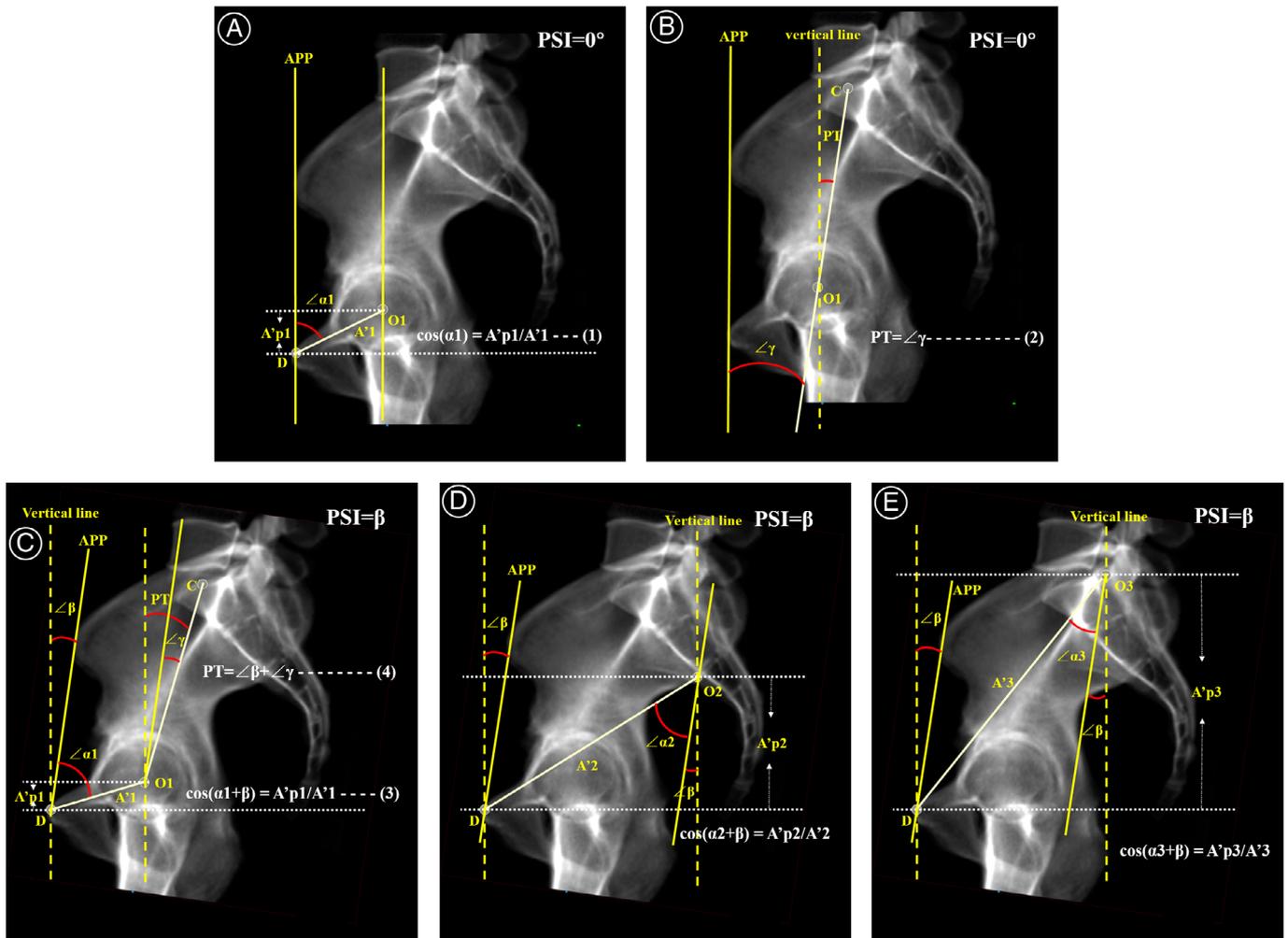


FIGURE 3 The principle of the inverse cosine function used to estimate the PSI. (A) A' , the projection of A' ($A'p$), and $\angle\alpha$ measured from the digitally reconstructed lateral radiographs have an inverse cosine function relationship. (B) When APP is parallel to vertical line, $\angle\gamma$ is equal to PT. (C) Function relationship between the parameters of pelvis with posterior tilt (β). (D) Inverse cosine function based on the lowest point of the inferior margin of sacroiliac joint (IMSJ). (E) Inverse cosine function based on the junction of iliac wing and superior articular process of S1 (JIS1)

Equation (3). The final calculation formula of the estimated PSI (ePSI) can then be defined as shown in Equation (5).

$$ePSI = \beta = \arccos\left(\frac{A'p}{[b * B']}\right) - \angle\alpha. \quad (5)$$

For individuals, the difference between PSI and PT is equal to the $\angle\gamma$, a fixed anatomical parameter. Since ASIS is not well characterized on pelvic lateral radiographs, we calculated the actual PSI (aPSI) with Equation (4) using the PT measured on the lateral radiograph and the anatomical angle $\angle\gamma$ measured from the pelvic model.

$$aPSI = \beta = PT - \gamma. \quad (6)$$

Statistics Analysis

The intra-observer and inter-observer reliabilities of the measurements were determined using the intra-class correlation coefficient (ICC). According to a previous study, ICC values of <0.40, 0.40–0.59, 0.60–0.74, and 0.75–1.00 were considered poor, fair, good, and excellent, respectively¹⁸.

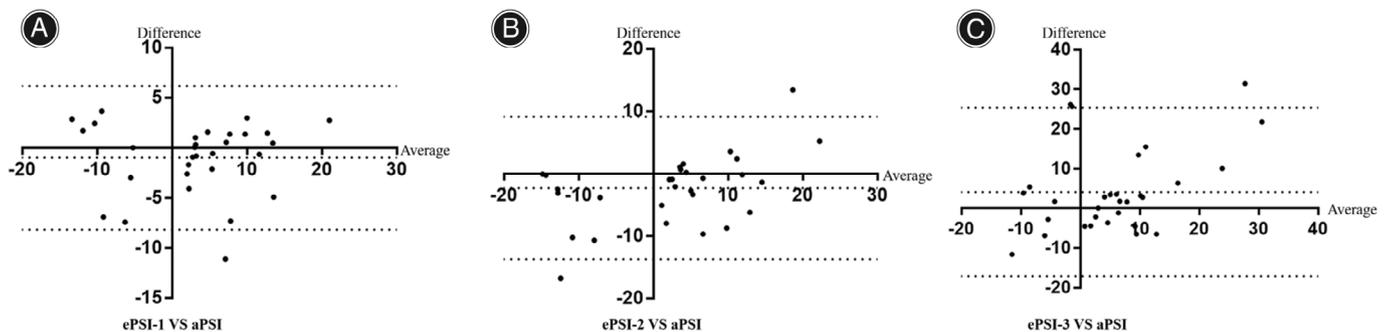
To assess the validity of this new method, the PSI values measured on each AP radiograph were compared to those measured on the lateral radiograph using a Pearson correlation test. The Bland–Altman plot was graphed to show the distribution of the differences between the estimated and actual PSI values. Statistical analysis was performed using SPSS 22.0 (IBM Corp, Armonk, NY). A p -value <0.05 indicated statistical significance.

TABLE 2 Comparison and reliability analysis between round 1 and round 2 of measurements

Parameters	Round 1 Mean (SD)	Round 2 Mean (SD)	Mean absolute difference (SD)	Inter-observer Reliability		Intra-observer Reliability	
				ICC	95% CI	ICC	95% CI
A1	50.20 (6.04)	49.22 (6.05)	1.58 (1.04)	0.943	0.906–0.993	0.978	0.929–0.993
A2	129.50 (10.22)	129.26 (9.53)	2.05 (1.32)	0.918	0.807–0.972	0.969	0.903–0.991
A3	157.10 (12.46)	156.90 (12.66)	0.86 (0.65)	0.987	0.968–0.996	0.992	0.973–0.997
B1	175.32 (10.92)	175.52 (10.70)	0.89 (0.88)	0.994	0.984–0.998	0.996	0.986–0.999
B2	90.28 (7.59)	90.36 (6.98)	1.25 (0.76)	0.952	0.852–0.985	0.962	0.882–0.988
B3	60.59 (4.94)	61.27 (4.64)	1.18 (0.72)	0.905	0.718–0.970	0.936	0.806–0.980
∠α1	76.15 (10.77)	77.39 (11.06)	3.12 (1.97)	0.941	0.860–0.980	0.990	0.968–0.997
∠α2	58.36 (6.76)	59.22 (6.69)	5.30 (3.27)	0.925	0.823–0.974	0.976	0.924–0.993
∠α3	33.42 (4.43)	33.67 (4.47)	2.77 (1.91)	0.896	0.761–0.964	0.960	0.876–0.988
∠γ	9.42 (6.36)	9.82 (6.15)	1.75 (1.2)	0.937	0.850–0.979	0.978	0.930–0.993
A'p1	0.63 (0.50)	0.48 (0.54)	0.16 (0.12)	0.963	0.885–0.989	0.986	0.962–0.995
A'p2	3.99 (0.93)	4.13 (0.83)	0.18 (0.23)	0.955	0.860–0.986	0.998	0.995–0.999
A'p3	7.47 (0.91)	6.89 (1.26)	1.07 (1.83)	0.482	–0.096–0.817	0.977	0.941–0.991
B'1	10.72 (1.15)	10.76 (1.16)	0.09 (0.08)	0.995	0.983–0.998	0.998	0.993–0.999
B'2	5.22 (0.62)	5.35 (0.77)	0.29 (0.20)	0.877	0.647–0.961	0.994	0.984–0.998
B'3	4.13 (1.15)	3.65 (0.31)	0.65 (0.95)	0.168	–0.400–0.643	0.854	0.653–0.943
PT	13.31 (4.26)	12.97 (4.23)	0.74 (0.55)	0.916	0.790–0.968	0.978	0.930–0.993
ePSI-1	1.74 (7.34)	0.20 (7.2)	1.77 (1.30)	0.886	0.801–0.960	0.975	0.921–0.992
ePSI-2	–1.15 (10.09)	–2.07 (9.97)	1.31 (0.89)	0.933	0.840–0.977	0.991	0.970–0.997
ePSI-3	4.20 (8.54)	3.03 (9.44)	2.19 (1.97)	0.568	0.239–0.823	0.951	0.849–0.985
aPSI	3.55 (7.67)	3.15 (7.61)	1.04 (0.81)	0.960	0.903–0.987	0.988	0.962–0.996

TABLE 3 Differences and correlation between ePSI and aPSI

Parameters	Mean absolute difference (SD)	Minimum absolute difference	Maximum absolute difference	r	p Value
ePSI-1	2.62 (2.56)	0.003	7.42	0.917	<0.001
ePSI-2	4.23 (4.35)	0.18	13.78	0.876	<0.001
ePSI-3	7.74 (8.12)	0.08	31.47	0.634	<0.003

**FIGURE 4** Bland–Altman plots describing the difference between ePSI and aPSI in three groups. (A) ePSI-1 vs aPSI. (B) ePSI-2 vs aPSI. (C) ePSI-3 vs aPSI

Results

Patients

Thirty patients with a mean age 59.33 ± 16.64 years (range 20–77 years) were included in this study. The male-to-female ratio was 3:2. The average time to complete a group of parameter measurements and calculation was 10.2 ± 1.8 min. It took only an average of 2.8 ± 1.1 min to

estimate the ePSI from AP radiographs, excluding the process of CT modeling and measurement.

Reliability

The mean values and reliability analysis of all parameters are shown in Table 2. Distance/angle parameters directly measured from the pelvic model and full-length spine

radiographs had good intra-observer reliability (0.806–0.999, $p < 0.001$) and inter-observer reliability (0.647–0.998, $p < 0.001$), except A/p3 and B'3. Both ePSI-1 and ePSI-2 had excellent inter- and intra-observer reliability (0.801–0.997, $p < 0.001$). The ePSI-3 estimated by the JIS1 related parameters had fair inter-observer reliability (0.239–0.823, $p < 0.001$). The corresponding inter- and intra-observer ICCs for aPSI were 0.903–0.987 and 0.962–0.996, indicating excellent reproducibility.

Validity

The mean (SD) absolute differences of ePSI-1, ePSI-2, and ePSI-3 estimated by the inverse cosine function were $2.62^\circ \pm 2.56^\circ$, $4.23^\circ \pm 4.35^\circ$, and $7.74^\circ \pm 8.12^\circ$, respectively (Table 3). The Pearson's correlation coefficient between ePSI-1 and aPSI was 0.917 ($p < 0.001$), which was higher than that between ePSI-2 ($r = 0.876$, $p < 0.001$) and ePSI-3 ($r = 0.634$, $p < 0.003$). The minimum absolute difference in the ePSI was less than 1° . The proportions of absolute difference of $<5^\circ$ for ePSI-1, ePSI-2, and ePSI-3 were 86.7%, 66.7%, and 56.7%, respectively. Bland–Altman plots demonstrating the differences between ePSI and aPSI are shown in Figure 4.

Discussion

In this study, the feasibility of the novel method based on the inverse cosine function has been confirmed by comparing the results of the new method and traditional method. And the differences between the ePSIs, including ePSI-1, ePSI-2, and ePSI-3, suggested that stability of the selected anatomical landmarks plays an essential role in guaranteeing the accuracy of PSI measurement.

Orientation of the Acetabular Component in THA

Most acetabular components are implanted empirically without accurate information regarding pelvic alignment. This may lead to malorientation of the acetabular component associated with postoperative implant impingement and dislocation. Sagittal inclination of the pelvis changes dynamically. Previous studies have shown clearly that PSI is different in the supine, standing, and sitting positions^{11,19}. This influences the functional position of the acetabular component. Moreover, pelvic sagittal alignment is dynamically variable after THA, and these changes persist into the 1-year postoperative period^{20,21}. Therefore, some researchers have suggested that it is not appropriate to determine the orientation of the acetabular component from anatomic landmarks due to the variability of PT. They recommend the evaluation of PSI as a reasonable method to determine the optimal orientation of the acetabular component^{1,19}.

There are two main methods for PSI estimation based on pelvic AP radiographs and pelvic CT. The first is the 2D/3D registration method, which is the method most used. Some researchers have used patient-specific CT to create digitally reconstructed radiographs, and compared them with the radiograph to estimate the relative position between the pelvis and the X-ray detector; they regarded these measurements as true values without validation^{19,22}. Recently, Jodeiri *et al.*²³

have developed a better 2D/3D registration method that estimates PSI angle from a single AP radiograph using two convolutional neural networks without requiring patient-specific CT; the results showed that 25% of the patients (118 cases) had larger errors ($6.14 \pm 2.38^\circ$). Although it appears to be an ideal method that requires only a single X-ray image, reliable accuracy verification for the 2D-3D registration technique is still lacking. There is an absence of matched pelvic lateral radiographs. Moreover, intraoperative real-time measurements of 2D/3D registration are impractical.

The second method is the measurement of anatomical landmark-related parameters. Kanazawa *et al.*¹² quantified the 3D pelvic position using the width and height ratio of the obturator foramina under various PTs and found that the height/width ratio had a linear regression with sagittal tilt. In another study, eight unique parameters/distances were measured to determine the most appropriate parameters for the calculation of PT¹³. Similarly, Uemura *et al.*¹⁴ evaluated five radiographic parameters and formed regression models to independently estimate the PSI in 50 patients. Although the correlation coefficients of the regression model for some parameters were very high, the maximum errors in the estimation of PSI for each parameter were still large ($\geq 17.7^\circ$). Taking the research reported by Uemura *et al.* as an example, the selected parameters included S-S distance, S-H distance, and the vertical diameter of the pelvic foramen on AP pelvic radiographs. These represent the projection of the corresponding anatomical parameters on the coronal plane. The length of these projected line segments changes with pelvic rotation, which is why these parameters are highly correlated with the PSI. According to mathematical principles, there is an inverse cosine function relationship between the anatomical parameters and their corresponding projected line segments based on the angle between the two line segments. Therefore, the relationship between PSI and the projected line segment is essentially an inverse cosine function, rather than a linear correlation.

Summary and Analysis of the Measurement Results

In this study, the inverse cosine function relationship between the three groups of anatomic and functional parameters was used as a substitute for the regression model. In contrast to ePSI-3, ePSI-1 and ePSI-2 had excellent inter- and intra-observer reliability. The reason for ePSI-3 being less reliable may be that sacral osteophytes and degeneration in the elderly have a greater impact on the identification of the junction of the iliac wing superior articular process of S1 (JIS1). Regarding accuracy, ePSI-1 had the smallest mean absolute difference (2.62° , less than 5°) and the highest correlation with aPSI ($r = 0.917$, $p < 0.001$). Compared to IMSJ and JIS1, the femoral head is easily identified on both AP radiographs and the CT model and is not susceptible to degeneration and osteoporosis, which can effectively improve measurement accuracy. The maximum absolute difference of ePSI-1 was 7.42° , which is smaller than the value reported by Uemura *et al.*¹⁴ (17.7°) and Muir *et al.*¹³ (14°). Although the Bland–Altman analysis demonstrated wide bounds for the

95% limits of agreement, 86.7% of the absolute difference of ePSI-1 was within 5° .

Notably, the maximum absolute difference in some measurements was greater than 10° . The main sources of error were as follows. First and foremost, IMSJ and JIS1 selected on CT reconstruction pelvic models are fixed points. The actual IMSJ and JIS1 change dynamically with variations in PT. This results in partial distortion of the measured parameters. Suppose that when the PSI is 0° , the IMSJ is located at a position similar to the 6 o'clock position of the dial. When there is anterior PT, the IMSJ may change to a position close to the 7 o'clock position of the dial, because the sagittal section of the IMSJ is curved. This is also one of the reasons for the large error in PSI estimation using the width/height ratio of obturator foramina¹². In addition, the value of ePSI-1 related parameters ($A'p1$) is relatively small, meaning that a small measurement error will result in a large calculation error. The second source of error is that the proficiency of the observers determines the accuracy of the measurement. Third, the poor quality of pelvic radiographs can result in an inaccurate identification of anatomical landmarks. Axial pelvic rotation on AP radiographs can cause inaccurate measurement of B' , which results in a large calculation error. Finally, the movement of the sacroiliac and hip joints is also a potential source of error. Therefore, it is necessary to improve the quality of pelvic AP radiographs and the observer proficiency to decrease measurement error.

Despite the use of both pelvic CT and full-length spine radiography, as shown in Equation (5), the value of ePSI was determined by $A'p/B'$. This varies with pelvic position and can be measured from full-length spine radiographs. Anatomical parameters b and $\angle\alpha$ are fixed constants in Equation (5), and are not affected by the change in PT. They can be accurately measured from the pelvic model based on pelvic CT. Furthermore, a standardized measurement process and stable and easily identifiable anatomical landmarks are reliable guarantees for reducing errors and improving repeatability.

Limitations

This study has some limitations. A total of 65% of the participants in this study were older than 60 years. Degeneration and osteoporosis of the pelvis might affect the quality of pelvic radiographs, and thus, increase measurement error. Conversely, examination of full-length spine AP and lateral radiographs must be performed twice. The change in body position could lead to a deviation between the actual PSI obtained using lateral radiographs and that estimated using AP radiographs. Finally, the principle of the measurement

method proposed in this study is relatively complex, which increases the workload of surgeons. Despite this, it is worthwhile to improve the accuracy of PSI measurements. Further combinations of deep learning frameworks or artificial intelligence technology may improve its accuracy and convenience.

Conclusion

Collectively, this novel method of PSI estimation based on the correct inverse cosine function, appropriate anatomical landmarks, and standardized methods of measurement is reliable and valid. It provides an alternative solution to evaluate the pelvis during preoperative planning and post-operative evaluation. Further studies to improve the convenience of this method are necessary.

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Conflicts of Interest

The authors have no conflicts of interest to declare.

Ethics Statement

This study was approved by Medical Ethics Committee of Shanghai Ninth People's Hospital (SH9H-2019-T80-2). An informed consent exemption was applied for this retrospective study, because it was difficult to contact the patients.

Author Contribution

Haohan Huang and Changqing Zhao designed the study. Haohan Huang and Yan Chen collected the data. Haohan Huang, Yan Chen, and Zhaoxun Chen analyzed the data and developed the methodology. Haohan Huang was a major contributor in writing the manuscript. Haohan Huang, Yan Cheng, Zhao-xun Chen, and Chang-qing Zhao analyzed and interpreted the patient's data. Chang-qing Zhao oversaw the study. Hao-han Huang and Yan Chen contributed equally to this work.

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Data Availability Statement

All data generated or analyzed during this case are included in this article.

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