■ HIP

Acetabular component position significantly influences the rebalancing of pelvic sagittal inclination following total hip arthroplasty in patients with Crowe type III/IV developmental dysplasia of the hip

H. Du,
H. Qiao,
Z. Zhai,
J. Zhang,
H. Li,
Y. Mao,
Z. Zhu,
J. Zhao,
D. Yu,
C. Zhao

From Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China

Aims

Sagittal lumbar pelvic alignment alters with posterior pelvic tilt (PT) following total hip arthroplasty (THA) for developmental dysplasia of the hip (DDH). The individual value of pelvic sagittal inclination (PSI) following rebalancing of lumbar-pelvic alignment is unknown. In different populations, PT regresses in a linear relationship with pelvic incidence (PI). PSI and PT have a direct relationship to each other via a fixed individual angle $\angle\gamma$. This study aimed to investigate whether the new PI created by acetabular component positioning during THA also has a linear regression relationship with PT/PSI when lumbar-pelvic alignment rebalances postoperatively in patients with Crowe type III/IV DDH.

Methods

Using SPINEPARA software, we measured the pelvic sagittal parameters including PI, PT, and PSI in 61 patients with Crowe III/IV DDH. Both PSI and PT represent the pelvic tilt state, and the difference between their values is $\angle\gamma$ ($PT = PSI + \angle\gamma$). The regression equation between PI and PT at one year after THA was established. By substituting $\angle\gamma$, the relationship between PI and PSI was also established. The Bland-Altman method was used to evaluate the consistency between the PSI calculated by the linear regression equation (ePSI) and the actual PSI (aPSI) measured one year postoperatively.

Results

The mean PT and PSI changed from preoperative values of 7.0° (SD 6.5°) and -8.0° (SD 6.7°), respectively, to 8.4° (SD 5.5°) and -4.5° (SD 5.9°) at one year postoperatively. This change shows that the pelvis tilted posteriorly following THA. In addition, when lumbar-pelvic alignment rebalanced, the linear regression equation between PI and PT was $PT = 0.45 \times PI - 10.5°$, and PSI could be expressed as $PSI = 0.45 \times PI - 10.5° - \angle\gamma$. The absolute difference between ePSI and aPSI was less than 5° in 55 of 61 patients (90.16%).

Conclusion

The new PI created by the positioning of the acetabular component significantly affects the PSI when lumbar-pelvic alignment changes and rebalances after THA in patients with Crowe III/IV DDH.

Cite this article: ***Bone Joint J*** **2025;107-B(2):149–156.**

Correspondence should be sent to C. Zhao; email: zhaocq9hospital@163.com

doi:10.1302/0301-620X.107B2.BJJ-2024-0485.R1 $2.00

Bone Joint J
2025;107-B(2):149–156.

Introduction

The anterior pelvic plane (APP), as described by DiGioia et al,[1] serves as an essential reference plane for surgeons during total hip arthroplasty (THA).[2] Pelvic sagittal inclination (PSI) is the angle between the APP and the vertical line, which influences the functional anteversion and inclination of the acetabular component.[1] Developmental

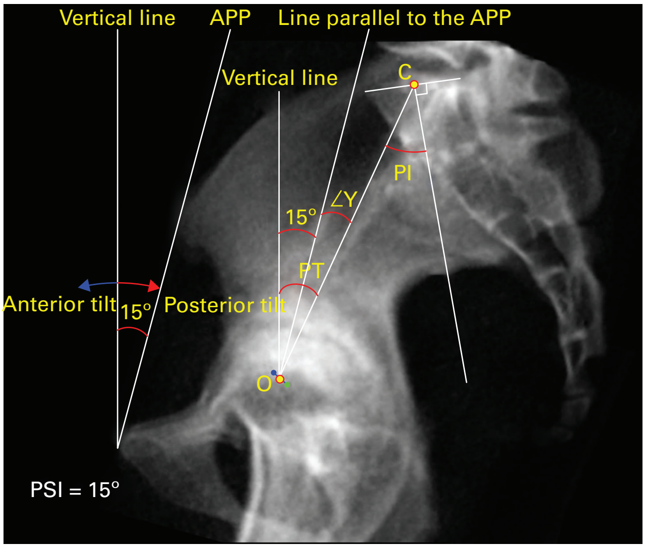

Fig. 1

The positional relationships of pelvic sagittal inclination (PSI), pelvic tilt (PT), ∠γ, and pelvic incidence (PI). ∠γ is defined as the angle between the line from the midpoint (O) of the bilateral femoral head to the midpoint of the sacral endplate (C) and the APP. PI is defined as the angle between the line connecting O to C and the vertical line of the sacral endplate.

dysplasia of the hip (DDH) encompasses a broad spectrum of abnormal hip development, ranging from mild acetabular dysplasia without hip dislocation to severe dysplasia, dislocation, and femoral head migration. Treatment of DDH ideally starts from infancy.[3] When THA is required to treat patients with untreated DDH and Crowe type III/IV dislocation,[4] there are significant anatomical abnormalities of the pelvis characterized by excessive tilt.[4,5] Selecting the appropriate acetabular position and orientation for component placement becomes a significant challenge. Suboptimum acetabular component position and orientation increases the risk of complications, such as dislocation, impingement, limitations in range of motion, and accelerated acetabular component wear, as shown in previous reports.[6–9] Other studies have shown that following periacetabular osteotomy or THA, patients with DDH experience posterior tilt of the pelvis and sagittal lumbar-pelvic alignment undergoes rebalancing, which may alter the anteversion angle of the acetabulum.[10–14] However, the precise PSI following this rebalancing has not been reported. If surgeons were able to predict the PSI in Crowe type III/IV DDH patients before placing the acetabular component, it could assist them in optimizing the implant's position and orientation.

In addition to PSI, another important parameter used to describe sagittal pelvic alignment is pelvic tilt (PT), a commonly used parameter in spinal surgery.[15] PT shares the same radiological significance as PSI and the difference between them lies in an anatomical parameter: the angle ∠γ. This angle is formed by the line connecting the midpoint of the hip axis to the centre of the sacral endplate and the APP, as illustrated in Figure 1. It can be measured for any individual patient with suitable computer software tools.[16]

Table I. Characteristics of 61 patients with developmental dysplasia of the hip.

Variable	**Crowe type III**		**Crowe type IV**		**p-value**
	Unilateral	**Bilateral**	**Unilateral**	**Bilateral**	
Patients, n	17	18	19	7	
Sex, n					0.205*
Female	17	16	15	7	
Male	0	2	4	0	
Mean age, yrs (SD)	53.5 (14.1)	46.7 (11.8)	47.8 (14.6)	51.6 (11.7)	0.433†
Mean BMI, kg/m² (SD)	23.2 (2.4)	24.7 (3.5)	22.9 (2.7)	23.4 (3.1)	0.276†

*Fisher's exact test.
†Analysis of variance.

Pelvic incidence (PI), as described by Legaye et al,[15] is the most important anatomical parameter to describe the sagittal lumbar-pelvic alignment. Geometrically, PI = PT + SS, where SS represents a dynamic measurement of the mobility of the lumbosacral-pelvic junction. The importance of PI, PT, and SS in lumbar-pelvic balance and alignment has been extensively studied.[17–19] Furthermore, studies on spinal sagittal alignment have consistently revealed a linear relationship between PI and PT across different populations, highlighting the strong dependency of PT on PI.[20–22] Recognizing the crucial role of PI and PT in evaluating lumbar-pelvic balance and alignment, many arthroplasty surgeons are now beginning to pay attention to these parameters.[23–26]

In THA for patients with Crowe type III/IV DDH, the hip joint centre of rotation, which has been displaced cranially due to the anterosuperior dislocation of the femoral head, is moved caudially with the aim of restoring the centre of rotation to as close to the normal anatomical position as possible.[27–30] As a result, a new PI is generated postoperatively. The new or proposed centre of rotation for the acetabular component can be simulated using software preoperatively.[16] If a linear correlation exists between PI and PT postoperatively when a rebalanced lumbar-pelvic relationship has evolved, it might be possible to estimate PT based on a preoperative simulated new PI and then calculate the specific value of PSI using the individual ∠γ.

The objectives of our study were to determine the changes in angle of PSI and PT following THA in patients with Crowe III/IV DDH, to analyze the relationship between PI, PT, and PSI in these patients, and develop a practical method to predict the degree of postoperative pelvic posterior tilt. This method will assist surgeons in optimizing the planned position and orientation of the acetabular prosthesis for patients undergoing THA for Crowe type III/IV DDH.

Methods

Definition of angles. PT reflects the sagittal position of the hip relative to the middle of the sacral endplate. A larger PT value indicates more posterior tilt of the pelvis, while a smaller PT value indicates more anterior tilt. Both PT and PSI are used to represent the sagittal tilt of the pelvis, with ∠γ representing the difference between them (PT = PSI + ∠γ) (Figure 1). The definitions of APP, PSI, PT, ∠γ, PI, and SS are shown in Supplementary Table i.

Table II. Values of pelvic sagittal parameters at different timepoints after total hip arthroplasty.

Variable	Preoperatively	1 week	p-value*	3 mths	p-value*	6 mths	p-value*	1 yr	p-value*
Patients, n	61	61		61		61		61	
Mean measurement, ° (SD)									
PI	44.4 (10.5)	42.4 (10.2)	< 0.001	42.4 (10.2)	< 0.001	42.4 (10.2)	< 0.001	42.4 (10.2)	< 0.001
PT	7.0 (6.5)	4.8 (6.5)	< 0.001	5.4 (6.7)	< 0.001	6.3 (6.3)	0.147	8.4 (5.5)	0.009
PSI	-8.0 (6.7)	-8.1 (6.3)	0.783	-7.5 (6.1)	0.075	-6.6 (5.8)	< 0.001	-4.5 (5.9)	< 0.001
Change in PT	N/A	-2.2 (3.5)	< 0.001	-1.7 (3.5)	< 0.001	-0.8 (4.1)	0.147	1.3 (3.8)	0.009
Change in PSI	N/A	-0.1 (1.8)	0.783	0.5 (2.1)	0.075	1.4 (2.8)	< 0.001	3.5 (3.2)	< 0.001

*Paired *t*-test.
N/A, not applicable; PI, pelvic incidence; PSI, pelvic sagittal inclination; PT, pelvic tilt.

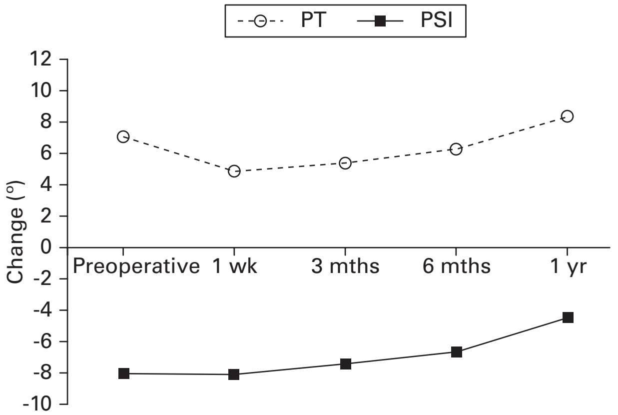

Fig. 2

Changes in pelvic tilt (PT) and pelvic sagittal inclination (PSI) at different timepoints. Compared with the preoperative values, PT and PSI showed an upward trend at one year after total hip arthroplasty.

Table III. Comparison of pelvic tilt and pelvic sagittal inclination between one year and one week postoperatively of patients with developmental dysplasia of the hip following total hip arthroplasty.

Variable	Crowe type III		Crowe type IV	
	Unilateral	Bilateral	Unilateral	Bilateral
Mean change in PT/PSI,° (SD)	3.3 (2.9)	3.8 (3.2)	3.1 (2.9)	4.6 (2.6)
PSI changes over 6.25°, n (%)	2/17 (11.76)	6/18 (33.33)	2/19 (10.53)	2/7 (28.57)

PSI, pelvic sagittal inclination; PT, pelvic tilt.

Patient selection. Approval for this study was provided by our institutional ethics committee. Informed consent was waived for this retrospective study. No identified characteristics were shown here. The clinical data of patients diagnosed with DDH at our hospital between September 2008 and September 2022 were retrospectively collected. The inclusion criteria were: patients with unilateral or bilateral Crowe type III/IV DDH; with no known lumbar spine disease; who underwent primary THA; who possessed complete preoperative and postoperative standing pelvic anteroposterior radiographs and supine pelvic CT scan data; and who had follow-up for a minimum of 12 months post-surgery. Exclusion criteria were any revision THA for DDH and a history of significant lumbar deformity or surgery, as these factors could influence the final lumbar-pelvic rebalancing. Revision THA patients (n = 4) were excluded because there may be more soft-tissue/bone loss compared to primary THA. Nine patients with less than 12 months of postoperative follow-up were also excluded. Following exclusions, a total of 61 patients were identified and included in the study.

Overall, 36 patients had unilateral high dislocation, ten patients had contralateral Crowe I/II hips, and 26 had contralateral normal hips. There were 25 patients with bilateral high dislocation DDH, with six undergoing one-stage bilateral THA and 19 undergoing interval THA at two to five months postoperatively. For bilateral cases, the time of completion of the second THA was considered the starting point for monitoring changes in PT during the follow-up. The demographic characteristics of patients with DDH are shown in Table I. No significant differences were found in terms of sex, age, or BMI across all patient groups. Consistent with previous literature,[31–33] the majority of our DDH cases were female.

Measurement and calculation of PT/PSI. The patients' 3D pelvic models were reconstructed using supine pelvic CT data and our engineers developed a software program, SPINEPARA, to assess and generate predictive data. The patients' acetabulums or femoral heads were matched by fitting spheres (Supplementary Figure a). The centres of the fitting spheres corresponded to the hip joint centre of rotation, and the software automatically outputted the patients' PI values (PI is a fixed anatomical parameter that is consistent in the standing, sitting, and supine position). Because the true acetabulums were dissociated from the femoral heads in patients with Crowe type III/IV DDH, we employed the centres of the femoral heads to represent the hip joints. After THA, the acetabular component and the femoral head formed concentric spherical structures, so their centre of rotation were consistent. In this study, we chose to match the acetabular components for postoperative analysis as the components are easier to identify on the pelvic models. Using our previously published inverse cosine function algorithm,[16] standing PT and PSI were measured and calculated via standing pelvic anteroposterior radiographs (Supplementary Figure b).

Clinical evaluation. The Harris Hip Score (HHS) was used to assess the hip function both preoperatively and at the final follow-up.[34] The patient's pain was measured using the visual analogue scale (VAS). Pain was rated on a scale from 0 to 10, where 0 indicated no pain and 10 represented unbearable or the worst imaginable pain.

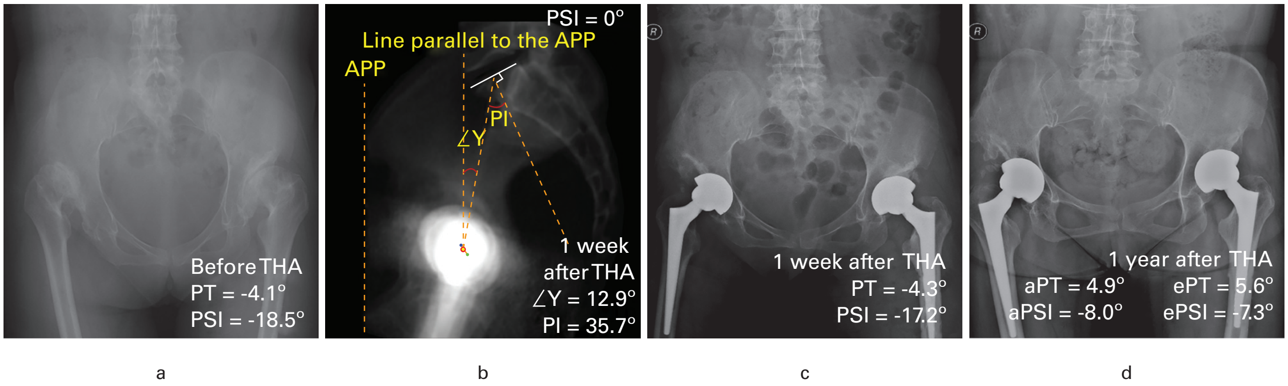

Fig. 3

Changes in pelvic sagittal parameters at different timepoints in a 58-year-old female patient. a) An anteroposterior pelvic radiograph taken before total hip arthroplasty (THA). b) A digitally reconstructed lateral radiograph showed the pelvic incidence (PI) and ∠γ one week after THA. c) Anteroposterior pelvic radiograph taken one week after THA. d) Anteroposterior pelvic radiograph taken one year after THA. The actual pelvic sagittal inclination (aPSI) and actual PT (aPT) represent the PT and PSI calculated by the inverse cosine function algorithm. The equational PT (ePT) was calculated by the equation PT = 0.45 × PI - 10.5°, and the ePSI was calculated by the equation: 0.45 × PI - 10.5° - ∠γ. With the PI measured at 35.7°, the calculated ePT was 5.6°, and with ∠γ at 12.9°, the calculated ePSI was -7.3°. Compared to one week post-THA, the aPSI of this patient increased by 9.2° at one year. APP, anterior pelvic plane.

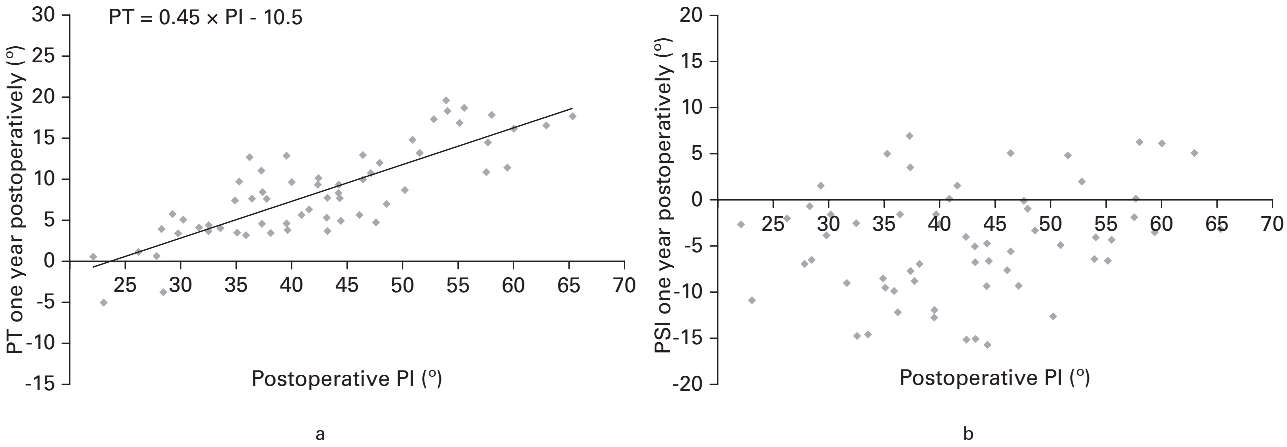

Fig. 4

Graph showing the correlation between pelvic incidence (PI) and pelvic tilt (PT), as well as between PI and pelvic sagittal inclination (PSI). a) A linear regression equation between PI and PT. r = 0.82; p < 0.001. b) No linear relationship was found between PI and PSI. r = 0.26; p = 0.045.

Establish the equation of PI and PT/PSI and assess its accuracy. Pearson's correlation coefficient test was employed to assess the linear relationship between PI and PT/PSI. To evaluate the accuracy of the equation, a Bland-Altman plot was created to show the distribution of the differences between the PSI as measured (ePSI) and the PSI calculated by the inverse cosine function algorithm (actual PSI; aPSI) of the 61 patients.

Statistical analysis. Continuous variables were summarized using means and SDs. Categorical variables were analyzed using Fisher's exact test. Analysis of variance (ANOVA) was used to compare the mean age and BMI across the different groups. The preoperative and postoperative PT and PSI were compared using paired *t*-tests. Due to the relatively small sample size of Crowe III/IV DDH patients with one-year follow-up, the significance level was set at $p < 0.01$ to achieve a higher statistical power. All analyses were conducted using SPSS v. 26.0 (IBM, USA).

Results

Changes in pelvic parameters after THA. The mean values of PI, PT, and PSI at different timepoints are shown in Table II. PT exhibited a significant reduction at one week and three months postoperatively compared to the preoperative values ($p < 0.001$, paired *t*-test). However, PT then gradually increased over time and surpassed the preoperative value by one year ($p = 0.009$, paired *t*-test). No significant difference was observed in PSI at one week ($p = 0.783$) and three months postoperatively ($p = 0.075$, paired *t*-test). However, PSI showed a significant

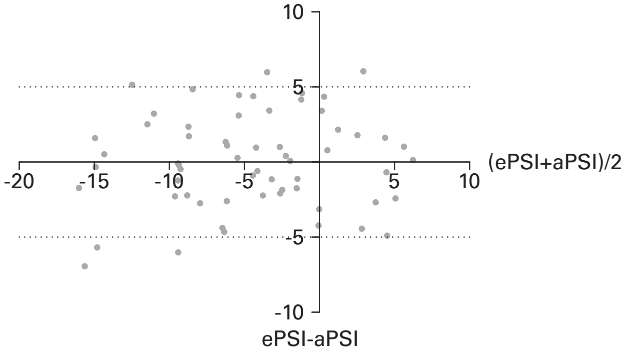

Fig. 5

Bland-Altman plot describing the difference between the pelvic sagittal inclination (PSI) calculated by the equation (ePSI) and the PSI calculated by the inverse cosine function algorithm (aPSI) of the 61 patients. The absolute difference between ePSI and aPSI was less than 5° in 55 of 61 patients (90.16%).

increase at six months and one year after the operation compared to the preoperative level ($p < 0.001$, paired *t*-test). The trends of PT and PSI are illustrated in Figure 2.

Previous studies reported that a change in acetabular anteversion greater than 5° is considered clinically significant, and each 5° change in PSI corresponds to a 4° change in acetabular anteversion.[35,36] PSI changes greater than 6.25° (5/0.8 = 6.25) are of significance. The changes in PT/PSI one year postoperatively compared to those at one week following THA in patients with DDH, and the proportion exceeding 6.25°, are presented in Table III. Among the 61 patients studied, 12 (19.67%) exhibited a change in PSI greater than 6.25°. Notably, patients with bilateral DDH demonstrated the most significant changes in PT/PSI values, as shown in Figure 3.

Correlation analysis. Simple linear regression analysis was applied to the PI, PT, and PSI values one year postoperatively. The analysis revealed a significant correlation between PI and PT, with a Pearson correlation coefficient of 0.82 ($p < 0.001$). The regression equation was $PT = 0.45 \times PI - 10.5°$, with a determination coefficient of $R^2 = 0.681$ (Figure 4a). No significant linear correlation was observed between PI and PSI, with a Pearson correlation coefficient of 0.26 ($p = 0.045$) (Figure 4b).

Verification. Figure 3d shows the difference between ePSI and aPSI. The Bland-Altman plots show the differences between the ePSI and the aPSI (Figure 5). The absolute difference between ePSI and aPSI was less than 5° in 55 out of 61 patients (90.16%).

Clinical outcomes. The mean HHS score improved significantly, increasing from 38.5 (SD 9.7) preoperatively to 92.5 (SD 4.1) at final follow-up. Correspondingly, the mean VAS score decreased significantly, from 4.7 points (SD 1.8) to 0.5 points (SD 0.6) ($p < 0.001$, paired *t*-test). No patients required revision THA during the follow-up period.

Discussion

There have been few studies investigating changes in the sagittal alignment of the pelvis after THA. Among those studies, the prevailing consensus suggests a posterior tilt of the pelvis after THA,[12,37] but also that these changes are unpredictable.[38] Studies specifically studying the change in PSI after THA in patients with DDH are rare, and their conclusions are consistent in reporting a posterior PT postoperatively.[12,13] PSI plays an important role in determining the anteversion and inclination of the acetabular component. Studies show that as the PSI increases by 5°, the acetabular anteversion angle will also increase by about 4°, which may cause impingement between the acetabular and femoral components and further cause an increase in the marginal load of the acetabular prosthesis.[35,36,39–42] Consequently, variations in PSI may increase the risk of complications, including dislocation, impingement, limited range of motion, and accelerated acetabular wear.[43,44] If the individual value of PSI can be predicted when lumbar-pelvic alignment rebalances and reaches its new position following THA, the change in PT can be compensated for when the acetabular component is positioned at operation.[45] However, in patients with DDH, particularly those with Crowe type III/IV, this compensation may assume greater significance and complexity, with resulting changes to the PI.

Moving the centre of rotation of the hip caudally during THA in patients with high-grade DDH results in changes to the PI and more complex changes to the PSI. Patients with Crowe type III/IV DDH, characterized by marked hip dislocation, exhibit a compensatory anterior tilt of the pelvis due to insufficient support for the anatomical acetabulum.[46,47] In this study, we included 61 patients. Their preoperative PT and PSI were 7.0° (SD 6.5°) and -8.0° (SD 6.7°), respectively. Our previous study has shown that the PT and PSI of healthy adults were 13.3° (SD 4.2°) and 3.5° (SD 7.6°), respectively.[16] The decrease in PT and PSI indicates that patients with Crowe type III/IV DDH have a compensatory anterior PT. At one week following THA, PT decreased significantly, whereas PSI did not. This could be attributed to the fact that THA caused a downward shift of the midpoint of the hip axis, while the pelvis had not tilted posteriorly significantly at that timepoint. From three months postoperatively, PT and PSI gradually increased and stabilized by one year. This confirms that the pelvis had tilted posteriorly, and the lumbar-pelvic alignment rebalancing has been achieved by one year. At the last follow-up, the PSI of unilateral Crowe type III, bilateral Crowe type III, unilateral Crowe type IV, and bilateral Crowe IV type DDH patients increased by 3.3°, 3.8°, 3.1°, and 4.6°, respectively, compared to one week after surgery. In our study, two of seven bilateral Crowe type IV patients and six of eighteen bilateral Crowe type III patients experienced a PSI change of more than 6.25° compared to one week after THA. We acknowledge that postoperative PT primarily affects the starting point of hip joint motion rather than the overall range of motion. However, when performing THA for high-grade DDH, if the acetabular component is placed with a different anteversion angle relative to the APP, the likelihood or risk of anterior instability and posterior impingement may vary depending on the initial acetabular component anteversion, as the pelvis tilts posteriorly during the first year. Therefore, in cases with bilateral Crowe type IV DDH, particular attention needs to be paid to acetabular component placement and anteversion, as proposed by Wang et al.[48]

We attribute posterior PT following THA to two main factors. First, THA aims to restore the hip to as normal an anatomical position as possible and relieve hip joint pain, and most patients demonstrated posterior PT postoperatively. Second, THA altered the relative positional relationship between the hip joint's axis of rotation and the centre of gravity of the trunk. The control of spinopelvic balance and alignment primarily involves the hips, the pelvis, and the upper half of the body trunk, which collectively undergo anterior and posterior tilting around the femoral head. In healthy young adults, the gravity line is 9 mm anterior to the axis of hip rotation. However, in patients with high-grade DDH, there is superior and anterior dislocation of the native femoral head, and the gravity line is relatively posterior to the axis of hip rotation. To compensate, these patients may exhibit anterior PT to bring the centre of gravity closer to the axis of hip rotation. Following THA, the anatomical position of hip joint is restored. Consequently, the centre of rotation of the hip joint now lies behind the gravity line, prompting a posterior tilt of the pelvis to bring the centre of gravity closer to the hip joint's centre of rotation. Compared to our findings, Zhang et al[13] investigated the change in the height and width ratio (H/W) of the obturator foramina before and after THA in patients with bilateral Crowe type IV DDH. They observed postoperative pelvic posterior tilt, similar to our results. Taki et al[12] compared the changes in pelvic tilt angle (PA) in standing and supine positions before and after THA over several years. They found that the mean PA change was 3.9° in the standing position and 2.7° in the supine position one year after surgery. A unique feature of our study is that we can calculate a specific PSI value for each patient when the lumbar-pelvic alignment is rebalanced. Previous studies reported the trends and variations of PT but did not provide the specific values of PSI, which are crucial to determining the functional anteversion and abduction of the acetabular component. Furthermore, if we can preoperatively predict the PSI of the rebalanced lumbar-pelvis, it will be of great value in choosing the optimum orientation of the acetabular component.

Previous studies have shown a linear correlation between PI and PT in healthy individuals or specific patient populations. For example, Yamato et al[20] studied the spine-pelvic parameters of 184 asymptomatic elderly individuals and found that the linear regression equation for optimal $PT = 0.47 \times PI - 7.5°$. Similarly, Sudhir et al[21] studied the spine-pelvic parameters of 101 asymptomatic adults and found a linear correlation between PT and PI with the equation $PT = -0.739° + 0.347 \times PI$. Lafage et al[22] analyzed the sagittal spinal radiological parameters of 179 spinal deformity patients and found that $PT = 1.14° + 0.71 \times PI - 0.52 \times (\text{maximal lumbar lordosis}) - 0.19 \times (\text{maximal thoracic kyphosis})$. By considering the linear correlation between PI and PT, PT and PSI are equivalent by $\angle\gamma$, and PI can be simulated preoperatively; the parameters PI, PT, and $\angle\gamma$ were therefore introduced in our study to try to predict the postoperative rebalanced PSI by establishing a mathematical relationship between PI and PSI. A similar linear regression relationship exists between PI and PT in our patients one year after THA. That is $PT = 0.45 \times PI - 10.5°$, with a Pearson correlation coefficient of 0.82 ($p < 0.001$). Although the Pearson correlation coefficient between PI and PSI was only 0.26 and no linear regression equation could be established between PI and PSI, the mathematical relationship between PI and PSI can still be expressed by introducing $\angle\gamma$, i.e. $PSI = 0.45 \times PI - 10.5° - \angle\gamma$.

Why is the linear correlation between PI and PT significant but the linear correlation between PI and PSI is not? The significant linear relationship between PI and PT following the rebalancing of lumbar-pelvic alignment can be explained by the following two factors. First, the patients studied were relatively young (mean age 49 years) and had no obvious underlying lumbar spine diseases, so the lumbar-pelvis could fully compensate for each other. Second, the inverse cosine function method we employed in our study demonstrated both high accuracy and high reliability. Our previous study reported that the difference between the PSI values calculated using the inverse cosine function method and the mean actual PSI values was 2.62° (SD 2.56°), which surpassed the 4.04° (SD 3.39°) margin observed with the deep learning framework algorithm proposed by Jodeiri et al.[49] The reason for the poor correlation between PI and PSI was that $\angle\gamma$ is not constant, but rather varies among individuals. Therefore, both PT and $\angle\gamma$ must be included to establish a mathematical relationship between PI and PSI. The predictive accuracy of the mathematical model was further studied through reliability analysis. Results showed that the difference between the absolute values of ePSI and aPSI was less than 5° in 90.16% of patients, indicating that the mathematical equation has a high predictive value.

At THA for DDH, different surgeons may choose different positions for the acetabular component. Some surgeons opt for placement on the posterosuperior aspect of the true acetabulum, while others choose to position the acetabular component on the superior portion of the true acetabulum. As a result, surgeons may produce varying new PI values postoperatively for the same patient.[27–30,50] This means that surgeons need to adopt different compensations when orientating the acetabular component. For instance, as shown in Figure 3, the patient's preoperative PSI was -18.5° and the ePSI was predicted to increase to -7.3° one year after surgery based on the new PI generated. Thus, subtracting about 9° from the acetabular anteversion angle as compensation was needed intraoperatively, as an 11.2° PSI change corresponds to approximately a 9° change in anteversion. Achieving this intraoperative adjustment in component anteversion may not be so technically challenging, particularly with the use of navigated instrumentation. We believe it is of crucial importance to preoperatively simulate and predict the change in PSI when the pelvis reaches a rebalanced state postoperatively, especially in patients undergoing bilateral THA for bilateral high dislocation and the aim of achieving anatomical placement of the acetabular components with optimum functional anteversion.

This study has several limitations. First, the sample size of this study was relatively small, with only 61 patients. This limitation is due to the rarity of the high-grade DDH, which makes it difficult to obtain a larger sample size. However, we carefully categorized the cases into subgroups (such as unilateral vs bilateral, and Crowe type III vs IV) and made efforts to identify potential risk factors. In the future, we hope to conduct studies with larger sample sizes or multicentre collaborations to further clarify and validate our findings. Second, the inverse cosine function method used in this study may initially appear complex, but its reliability and validity have been previously confirmed. Further confirmatory studies by others may lead to its general acceptance. Finally, we used the standing pelvic anteroposterior radiographs and supine pelvic CT data combined with the inverse cosine function algorithm to calculate the patient's PSI. However, PSI is best studied through lateral standing radiographs, which are not routinely taken during follow-up after THA. Therefore, we recommend that surgeons conduct lateral pelvic radiographs in supine, sitting, and standing positions as part of the routine imaging examinations for Crowe type III/IV DDH patients, both preoperatively and postoperatively, as suggested by Yang et al.[5]

In summary, this study proposes a method to predict the PSI when lumbar-pelvic alignment has rebalanced in patients with Crowe type III/IV DDH after THA. When planning the acetabular component position, surgeons should also plan for acetabular component orientation that takes into account subsequent lumbopelvic realignment through the mathematical equation $PSI = 0.45 \times PI - 10.5^\circ - \angle\gamma$. The calculated and predicted value of PI simulated before surgery can predict the PSI when lumbar-pelvic alignment has rebalanced following THA for Crowe III/IV DDH patients. This may lead to fewer complications and improve patient outcomes.

Take home message

- After total hip arthroplasty, Crowe type III/IV developmental dysplasia of the hip patients will have pelvic posterior tilt and lumbar-pelvic rebalance.
- A linear correlation exists between pelvic incidence (PI) and pelvic tilt at the lumbar-pelvic rebalanced stage.
- The new PI which could be simulated before surgery could predict the pelvic sagittal inclination at the rebalanced stage.

Supplementary material

The descriptions of spinopelvic parameters and the detailed process of calculating pelvic tilt and pelvic sagittal inclination.

References

1. **DiGioia AM**, **Hafez MA**, **Jaramaz B**, **Levison TJ**, **Moody JE**. Functional pelvic orientation measured from lateral standing and sitting radiographs. *Clin Orthop Relat Res.* 2006;453:272–276.
2. **Wan Z**, **Malik A**, **Jaramaz B**, **Chao L**, **Dorr LD**. Imaging and navigation measurement of acetabular component position in THA. *Clin Orthop Relat Res.* 2009;467(1):32–42.
3. **Theunissen WWES**, **Van der Steen MC**, **Van Veen MR**, **Van Douveren FQMP**, **Witlox MA**, **Tolk JJ**. Strategies to optimize the information provision for parents of children with developmental dysplasia of the hip. *Bone Jt Open.* 2023;4(7):496–506.
4. **Jawad MU**, **Scully SP**. In brief: Crowe's classification: arthroplasty in developmental dysplasia of the hip. *Clin Orthop Relat Res.* 2011;469(1):306–308.
5. **Yang G**, **Li Y**, **Zhang H**. The influence of pelvic tilt on the anteversion angle of the acetabular prosthesis. *Orthop Surg.* 2019;11(5):762–769.
6. **Goel A**, **Lau EC**, **Ong KL**, **Berry DJ**, **Malkani AL**. Dislocation rates following primary total hip arthroplasty have plateaued in the Medicare population. *J Arthroplasty.* 2015;30(5):743–746.
7. **Lewinnek GE**, **Lewis JL**, **Tarr R**, **Compere CL**, **Zimmerman JR**. Dislocations after total hip-replacement arthroplasties. *J Bone Joint Surg Am.* 1978;60-A(2):217–220.
8. **Yoshimine F**. The safe-zones for combined cup and neck anteversions that fulfill the essential range of motion and their optimum combination in total hip replacements. *J Biomech.* 2006;39(7):1315–1323.
9. **Wan Z**, **Boutary M**, **Dorr LD**. The influence of acetabular component position on wear in total hip arthroplasty. *J Arthroplasty.* 2008;23(1):51–56.
10. **Ma H-Y**, **Lu Q**, **Sun J-Y**, **et al**. One-stage total hip arthroplasty with modular S-ROM stem for patients with bilateral Crowe type IV developmental dysplasia. *Orthop Surg.* 2020;12(6):1913–1922.
11. **Du Y-Q**, **Sun J-Y**, **Ma H-Y**, **Wang S**, **Ni M**, **Zhou Y-G**. Leg length balance in total hip arthroplasty for patients with unilateral Crowe type IV developmental dysplasia of the hip. *Orthop Surg.* 2020;12(3):749–755.
12. **Taki N**, **Mitsugi N**, **Mochida Y**, **Akamatsu Y**, **Saito T**. Change in pelvic tilt angle 2 to 4 years after total hip arthroplasty. *J Arthroplasty.* 2012;27(6):940–944.
13. **Zhang B**, **Du Y**, **Sun J**, **Shen J**, **Li T**, **Zhou Y**. Change of pelvic sagittal tilt after total hip arthroplasty in patients with bilateral Crowe type IV developmental dysplasia of the hip. *Orthop Surg.* 2022;14(5):919–926.
14. **Thummala AR**, **Xi Y**, **Middleton E**, **Kohli A**, **Chhabra A**, **Wells J**. Does surgery change pelvic tilt? An investigation in patients with osteoarthritis of the hip, dysplasia, and femoroacetabular impingement. *Bone Joint J.* 2022;104-B(9):1025–1031.
15. **Legaye J**, **Duval-Beaupère G**, **Hecquet J**, **Marty C**. Pelvic incidence: a fundamental pelvic parameter for three-dimensional regulation of spinal sagittal curves. *Eur Spine J.* 1998;7(2):99–103.
16. **Huang H-H**, **Chen Y**, **Chen Z-X**, **Zhao C-Q**. Reliability and validity analysis of pelvic sagittal inclination calculated by inverse cosine function method on pelvic anteroposterior radiographs. *Orthop Surg.* 2022;14(10):2721–2729.
17. **Ike H**, **Bodner RJ**, **Lundergan W**, **Saigusa Y**, **Dorr LD**. The effects of pelvic incidence in the functional anatomy of the hip joint. *J Bone Joint Surg Am.* 2020;102-A(11):991–999.
18. **Grammatopoulos G**, **Falsetto A**, **Sanders E**, **et al**. Integrating the combined sagittal index reduces the risk of dislocation following total hip replacement. *J Bone Joint Surg Am.* 2022;104-A(5):397–411.
19. **Heckmann N**, **McKnight B**, **Stefl M**, **Trasolini NA**, **Ike H**, **Dorr LD**. Late dislocation following total hip arthroplasty: spinopelvic imbalance as a causative factor. *J Bone Joint Surg Am.* 2018;100-A(21):1845–1853.
20. **Yamato Y**, **Hasegawa T**, **Kobayashi S**, **et al**. Calculation of the target lumbar lordosis angle for restoring an optimal pelvic tilt in elderly patients with adult spinal deformity. *Spine (Phila Pa 1976).* 2016;41(4):E211–7.
21. **Sudhir G**, **Acharya S**, **K L K**, **Chahal R**. Radiographic analysis of the sacropelvic parameters of the spine and their correlation in normal asymptomatic subjects. *Global Spine J.* 2016;6(2):169–175.
22. **Lafage V**, **Schwab F**, **Vira S**, **Patel A**, **Ungar B**, **Farcy J-P**. Spino-pelvic parameters after surgery can be predicted: a preliminary formula and validation of standing alignment. *Spine (Phila Pa 1986).* 1976;36(13):1037–1045.
23. **Bodner RJ**. The functional mechanics of the acetabular component in total hip arthroplasty. *J Arthroplasty.* 2022;37(11):2199–2207.
24. **Heckmann N**, **Tezuka T**, **Bodner RJ**, **Dorr LD**. Functional anatomy of the hip joint. *J Arthroplasty.* 2021;36(1):374–378.
25. **Gu M**, **Zhang Z**, **Kang Y**, **et al**. Roles of sagittal anatomical parameters of the pelvis in primary total hip replacement for patients with ankylosing spondylitis. *J Arthroplasty.* 2015;30(12):2219–2223.
26. **Vigdorchik JM**, **Madurawe CS**, **Dennis DA**, **Pierrepont JW**, **Jones T**, **Huddleston JI**. High prevalence of spinopelvic risk factors in patients with post-operative hip dislocations. *J Arthroplasty.* 2023;38(4):706–712.
27. **Iwase T**, **Morita D**, **Ito T**, **Takemoto G**, **Makida K**. Favorable results of primary total hip arthroplasty with acetabular impaction bone grafting for large segmental bone defects in dysplastic hips. *J Arthroplasty.* 2016;31(10):2221–2226.
28. **Xu J**, **Xu C**, **Mao Y**, **Zhang J**, **Li H**, **Zhu Z**. Posterosuperior placement of a standard-sized cup at the true acetabulum in acetabular reconstruction of developmental dysplasia of the hip with high dislocation. *J Arthroplasty.* 2016;31(6):1233–1239.
29. **Liu B**, **Gao Y-H**, **Ding L**, **Li S-Q**, **Liu J-G**, **Qi X**. Computed tomographic evaluation of bone stock in patients with Crowe type III developmental dysplasia of the hip: implications for guiding acetabular component placement using the high hip center technique. *J Arthroplasty.* 2018;33(3):915–918.
30. **Hartofilakidis G**, **Stamos K**, **Karachalios T**. Treatment of high dislocation of the hip in adults with total hip arthroplasty. Operative technique and long-term clinical results. *J Bone Joint Surg Am.* 1998;80-A(4):510–517.
31. **Pollet V**, **Percy V**, **Prior HJ**. Relative risk and incidence for developmental dysplasia of the hip. *J Pediatr.* 2017;181:202–207.
32. **Zhu D**, **Zhu H**. Incidence and epidemiological characters of developmental dysplasia of the hip in Lianyungang: based on ultrasound screening: a retrospective study. *Int J Gen Med.* 2022;15:8547–8555.
33. **Xiao H**, **Tang Y**, **Su Y**. Risk factors of developmental dysplasia of the hip in a single clinical center. *Sci Rep.* 2022;12(1):19461.

34. **Harris WH**. Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty. An end-result study using a new method of result evaluation. *J Bone Joint Surg Am*. 1969;51-A(4):737–755.
35. **Babisch JW**, **Layher F**, **Amiot L-P**. The rationale for tilt-adjusted acetabular cup navigation. *J Bone Joint Surg Am*. 2008;90-A(2):357–365.
36. **Schloemann DT**, **Edelstein AI**, **Barrack RL**. Changes in acetabular orientation during total hip arthroplasty. *Bone Joint J*. 2019;101-B(6_Supple_B):45–50.
37. **Innmann MM**, **Verhaegen JCF**, **Reichel F**, **Schaper B**, **Merle C**, **Grammatopoulos G**. Spinopelvic characteristics normalize 1 year after total hip arthroplasty: a prospective, longitudinal, case-controlled study. *J Bone Joint Surg Am*. 2022;104-A(8):675–683.
38. **Kazarian GS**, **Schloemann DT**, **Barrack TN**, **Lawrie CM**, **Barrack RL**. Pelvic rotation after total hip arthroplasty is dynamic and variable. *Bone Joint J*. 2020;102-B(7_Supple_B):47–51.
39. **Lembeck B**, **Mueller O**, **Reize P**, **Wuelker N**. Pelvic tilt makes acetabular cup navigation inaccurate. *Acta Orthop*. 2005;76(4):517–523.
40. **Haenle M**, **Heitner A**, **Mittelmeier W**, **et al**. Assessment of cup position from plain radiographs: impact of pelvic tilting. *Surg Radiol Anat*. 2007;29(1):29–35.
41. **Parratte S**, **Pagnano MW**, **Coleman-Wood K**, **Kaufman KR**, **Berry DJ**. The 2008 Frank Stinchfield award: variation in postoperative pelvic tilt may confound the accuracy of hip navigation systems. *Clin Orthop Relat Res*. 2009;467(1):43–49.
42. **Maratt JD**, **Esposito CI**, **McLawhorn AS**, **Jerabek SA**, **Padgett DE**, **Mayman DJ**. Pelvic tilt in patients undergoing total hip arthroplasty: when does it matter? *J Arthroplasty*. 2015;30(3):387–391.
43. **Zhu J**, **Shen C**, **Chen X**, **Cui Y**, **Peng J**, **Cai G**. Total hip arthroplasty with a non-modular conical stem and transverse subtrochanteric osteotomy in treatment of high dislocated hips. *J Arthroplasty*. 2015;30(4):611–614.
44. **Ollivier M**, **Abdel MP**, **Krych AJ**, **Trousdale RT**, **Berry DJ**. Long-term results of total hip arthroplasty with shortening subtrochanteric osteotomy in Crowe IV developmental dysplasia. *J Arthroplasty*. 2016;31(8):1756–1760.
45. **Tsukamoto M**, **Kawasaki M**, **Suzuki H**, **Fujitani T**, **Sakai A**. Proposal of accurate cup placement procedure during total hip arthroplasty based on pelvic tilt discrepancies in the lateral position. *Sci Rep*. 2021;11(1):13870.
46. **Ren P**, **Kong X**, **Chai W**, **Wang Y**. Sagittal spinal-pelvic alignment in patients with Crowe type IV developmental dysplasia of the hip. *BMC Musculoskelet Disord*. 2020;21(1):688.
47. **Tannast M**, **Fritsch S**, **Zheng G**, **Siebenrock KA**, **Steppacher SD**. Which radiographic hip parameters do not have to be corrected for pelvic rotation and tilt? *Clin Orthop Relat Res*. 2015;473(4):1255–1266.
48. **Wang S**, **Zhou Y**, **Ma H**, **Du Y**, **Piao S**, **Wu W**. Mid-term results of total hip replacement with subtrochanteric osteotomy, modular stem, and ceramic surface in Crowe IV hip dysplasia. *Arthroplast Today*. 2018;4(3):363–369.
49. **Jodeiri A**, **Zoroofi RA**, **Hiasa Y**, **et al**. Fully automatic estimation of pelvic sagittal inclination from anterior-posterior radiography image using deep learning framework. *Comput Methods Programs Biomed*. 2020;184:105282.
50. **Paavilainen T**, **Hoikka V**, **Solonen KA**. Cementless total replacement for severely dysplastic or dislocated hips. *J Bone Joint Surg Br*. 1990;72-B(2):205–211.

Author information:
H. Du, MD, Orthopaedic Surgeon
H. Qiao, MD, PhD, Orthopaedic Surgeon
Z. Zhai, MD, PhD, Orthopaedic Surgeon
J. Zhang, MD, PhD, Orthopaedic Surgeon
H. Li, MD, PhD, Orthopaedic Surgeon
Y. Mao, MD, PhD, Orthopaedic Surgeon
Z. Zhu, MD, PhD, Orthopaedic Surgeon
J. Zhao, MD, PhD, Orthopaedic Surgeon
D. Yu, MD, PhD, Orthopaedic Surgeon
C. Zhao, MD, PhD, Orthopaedic Surgeon
Department of Orthopaedic Surgery, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China; Shanghai Key Laboratory of Orthopaedic Implants, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China.

Author contributions:
H. Du: Formal analysis, Writing – original draft.
H. Qiao: Data curation, Software, Writing – original draft.
Z. Zhai: Formal analysis, Investigation, Resources, Writing – review & editing.
J. Zhang: Formal analysis, Investigation, Writing – review & editing.
H. Li: Formal analysis, Methodology, Supervision, Writing – review & editing.
Y. Mao: Formal analysis, Investigation, Project administration, Software, Writing – review & editing.
Z. Zhu: Formal analysis, Investigation, Validation, Writing – review & editing.
J. Zhao: Formal analysis, Investigation, Methodology, Validation, Writing – review & editing.
D. Yu: Conceptualization, Investigation, Methodology, Validation, Writing – review & editing.
C. Zhao: Conceptualization, Methodology, Supervision, Visualization, Writing – review & editing.

H. Du and H. Qiao are joint first authors.

D. Yu and C. Zhao are joint senior authors.

Funding statement:
The authors received no financial or material support for the research, authorship, and/or publication of this article.

ICMJE COI statement:
The authors declare there are no conflicts of interest regarding the publication of this paper.

Data sharing:
The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Ethical review statement:
Ethical approval for this study was provided by the Ethics Committee of our institution. Informed consent has been waived with the approval of the Ethics Committee as this is a retrospective study.

Open access funding:
The authors confirm that the open access fee for this study was self-funded.

This article was primary edited by D. Johnstone.