Clinical Impact of Pelvic Malrotation on Radiograph-Based Preoperative Planning for Total Hip Arthroplasty: A Proof-of-Concept and Prudent Prediction of Acceptable Rotation

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Abstract

Introduction Pelvic rotation (PR) on preoperative radiograph templating can affect various critical measured acetabular angles and potentially outcomes of successful total hip arthroplasty (THA). Optimising anatomical reconstruction of the joint is essential to achieve function, longevity and prevention of complications following surgery. There is limited literature that standardises the degree of acceptable PR on radiograph or its effects on the fitting of acetabular prostheses.

Objective This study aimed to develop a proof-of-concept that quantifies how PR can affect various acetabular angles used in pre-operative THA templating and to formulate a practicable method of determining if the preoperative PR is acceptable.

Materials and methods Computerised tomography (CT) models from three control and two THA patients were generated and manipulated in various degrees of PR. CT slices were thickened to simulate radiographs and acetabular angles measured.

Results The acetabular anteversion distance (AAD) and lateral opening angle (LOA) demonstrated a linear and quadratic relationship with good correlation ($R^2 = 0.923$, $R^2 = 0.710$ respectively, $p < 0.0001$) in relation to PR. Change in area of prosthesis (AOP) demonstrated a good linear correlation ($r^2 = 0.774$ and $r^2 = 0.875$, $p < 0.0001$) with PR. Two novel measurements were used to estimate the degree of PR from a pelvic radiograph; the horizontal distance between pubic symphysis and middle of sacrococygeal joint (PSSC) and the simplified pelvic rotation ratio (SPRR). A strong correlation between PSSC and SPRR with change in PR was observed ($R^2 = 0.970$, $R^2 = 0.953$, $p < 0.001$).

Conclusion Preliminary result suggests that an SPRR > 2.0 correlates to PR > 20° with potential to have a clinical impact on preoperative measurements.

Keywords Radiograph · X-ray · Pelvic · Rotation · Hip · Arthroplasty · Preoperative planning · Acetabular angle · Computerised tomography

Abbreviations

3D Three-dimensional
AAD Acetabular anteversion distance
AD Acetabular diameter
AIA Acetabular inclination angle
ANOVA Analysis of variance
AOP Area of prosthesis
CT Computerised tomography
ER External rotation
HASIS Horizontal distance between the two anterior superior iliac spines
IR Internal rotation
LOA Lateral opening angle
PACS Picture archiving and communications systems
PR Pelvic rotation
PSSC Horizontal distance between pubic symphysis and middle of sacrococygeal joint
RIS Radiology information system
ROM Range of movement
SPRR Simplified pelvic rotation ratio
SPSS Statistical package for the social sciences
THA Total hip arthroplasty

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**Background**

Total hip arthroplasty (THA) is a well-established method to treat hip pain and physical limitations due to osteoarthritis and other medical conditions. The acetabular prosthesis implantation angle affects muscle strength, gait, limb lengths, impingement, noise generation, loosening, postoperative range of movement (ROM) and is related to dislocation and liner wear [1–7]. Optimising biomechanical and anatomical reconstruction of the joint is essential to achieve function, longevity and prevention of complications following surgery [1–7]. Preoperative templating from a plain anterior–posterior radiograph is the primary method for initial evaluation and cornerstone for prosthesis positioning. However, such images are subject to patient pelvic tilt and rotation. Suboptimal acetabular component position significantly impacts the results of a hip arthroplasty, including increased risk of instability, impingement, dislocation and cup failure [1, 3, 6, 8–13]. Correct template positioning influences the accuracy of acetabular cup placement planning and long-term success of the total hip arthroplasty [6].

Effects of pelvic position on pelvic tilt have been well studied [14–16]. When the pelvis tilts posteriorly, the anteversion and abduction angles of the acetabular implant increase, potentially leading to excessive wear due to neck impingement and edge loading, with increased risk of anterior dislocation [6]. Prediction of pelvic displacement before surgery is therefore essential for accurate placement of the acetabular implant.

Babisch et al. demonstrated that acetabular cup positions are affected by pelvic tilt on computerised tomography (CT) models, with good accuracy and reproducibility [17]. Similarly, a previous study used a computer-generated three-dimensional (3D) model to determine the effect of pelvic tilt on acetabular angles [18]. The functional angle of the acetabular implant is related to the pelvic tilt angle, with the anteversion angle of the acetabular implant changing by approximately 0.7° with every degree in change in pelvic inclination.

In contrast, there is a lack of literature describing the isolated effects of radiographic pelvic rotation (PR) on preoperative acetabular angulation of acetabular prostheses. The purpose of this study was to generate 3D CT pelvis models from healthy controls and arthroplasty patients and to quantify the potential effects of pelvic rotation on acetabular cup position in various planes. Furthermore, this study aimed to determine if there was a simple and practicable method of determining pelvic rotation on pre-operative templating. This proof-of-concept study hypothesised that PR may have detrimental impacts on acetabular angles during preoperative planning for THA.

It also hypothesised that actual PR can be estimated from recreated plain radiographs using simple measurements and anatomical landmarks.

**Methods**

**Study Design**

This was a retrospective case–control experimental design to investigate the effect of PR on acetabular angulation.

**Participants and Setting**

To establish a proof-of-concept, a convenience sample of control and patients undergoing total hip arthroplasty (THA) due to osteoarthritis from the Royal Adelaide Hospital was selected between the 1 January 2016 and 31 June 2018. In total, five patient’s pelvic CT images were analysed, with three controls and two THA patients. The control patient CT results were confirmed normal with no abnormalities by consultant radiologist prior to inclusion in the study. The THA CT images were also confirmed to be otherwise normal prior to inclusion. Baseline patient characteristics are recorded in Table 1. Definitions used to describe the angles and measurements used in this study can be found in Table 2. By neutralising pelvic tilt completely, the potential confounding effects of pelvic tilt on acetabular angles are ameliorated.

**Assessment of Pelvic Rotation Using Computerised Model**

True pelvic rotation was established using Carestream Picture Archiving and Communications Systems (PACS) and Radiology Information System (RIS) version 11. 0.14.35. For the acquisition of the images used in this study, thickened CT slices were used to simulate the X-ray radiographs.

| Table 1 | Baseline characteristics of participating patients |
|---------|-----------------------------------------------|
| Patient demographics | Control | THR | Sig. (p) |
| Number of participants: (M/F) | 3 (3/0) | 2 (0/2) | 0.1 |
| Age years: mean (SD) | 45 (31.19) | 58 (28.28) | 0.699 |
| Past medical history of: (n) | | | |
| Hip Osteo-Arthritis | 1 | 2 | 0.400 |
| Osteoporosis | 0 | 1 | 0.400 |
| T2DM | 0 | 1 | 0.400 |
| Heart Failure | 0 | 1 | 0.400 |
| Corticosteroid use | 0 | 1 | 0.400 |
| THR side (L:R) | (0:1) | (2:1) | 1.0 |
in a 2-dimensional plane. The CT reconstruction was manipulated at varying degrees of rotation from the neutral position. The neutral PR was defined by ischiotuberosities being parallel to reference [19]. All pelvic images were aligned with a neutral pelvic tilt as described by Marratt et al. [18]. All parameters were measured on left hips. Pelvic rotation at increments of 10° was performed up to 60° to optimise interpretation data. Rotation was defined as positive (+) rotation corresponding to pelvic rotation to the left (relative pelvic External Rotation, ER) and negative (−) rotation corresponding to pelvic rotation to the right (Internal rotation, IR). At each 10° increment, the AP and lateral 2-dimensional

| Measurement                                   | Definition                                                                                                                                                                                                 |
|-----------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Neutral pelvic rotation                       | Vertical alignment of the centre of the sacroccocygeal joint with the middle of the pubic symphysis                                                                                                       |
| Acetabular anteversion distance (AAD)         | A sphere was drawn over the femoral head. Two perpendicular lines were drawn, intersecting at the centre of the femoral head and angled at +45 and -45 degrees to the vertical axis. The acetabular anteversion distance was defined as the anterior and posterior acetabulum rims distance, measured in the same plane as the middle point, parallel to the +45 degree line drawn |
| Acetabular inclination angle (AIA)            | The acute angle intersecting a vertical line drawn through the medial wall of the acetabulum and a diagonal line connecting the medial and lateral surface of the acetabulum.                                         |
| Lateral opening angle (LOA), Also known as Sharp’s angle [19] [20] | The acute angle formed by the horizontal line connecting the “teardrop” of the acetabulum on both sides and the diagonal line connecting the medial and lateral surfaces of the acetabulum.                              |
| Area of prosthesis (AOP)                      | The prosthesis was outlined, and two-dimensional area calculated                                                                                                                                     |
| Acetabular diameter (AD)                      | The distance between the medial and lateral acetabulum cup margins The length of the diagonal line connecting the medial and lateral surface of the acetabulum                                                                 |
| PSSC                                          | Horizontal distance between pubic symphysis (PS) and middle of sacroccocygeal (SO) joint (mm) [21]                                                                                                |
| HASIS                                         | Horizontal distance between the left and right anterior superior iliac spines (ASIS) (mm)                                                                                                |
| Simplified pelvic rotation ratio (SPRR)        | Horizontal distance between pubic symphysis and middle of sacroccocygeal joint (PSSC) divided by the horizontal distance between the left and right ASIS                                                                 |
XR images of the pelvis were recorded. Respective angles, measurements and ratio calculations were undertaken using the definitions summarised in Table 2.

**Pelvic Rotation (PR)**

PR on AP radiograph was estimated using the horizontal distance between the pubic symphysis and middle of the sacroccocygeal joint (PSSC) using the methods described in Tannast et al. [20]. We proposed a refined method for PR assessment using the ratio between the PSSC and the horizontal distance between the two anterior superior iliac spines (HASIS), thus allowing a more patient-specific determination. We named this measurement the simplified pelvic rotation ratio (SPRR).

**Statistical Analysis**

Statistical analysis was performed with the Statistical Package for the Social Sciences (SPSS) for Windows, Version 24.0, IBM Corp. Released 2016. Armonk, NY. A highly precise value of \( p < 0.001 \) was accepted as indicating statistical significance. Data were expressed as mean ± standard deviation for continuous variables and as a number and percentage for categorical variables. Categorical data between the groups were compared using the Chi-squared test or Fisher’s exact test, whilst continuously distributed data were compared using either a Mann–Whitney U test or an analysis of variance (ANOVA). Linear and quadratic trend lines were generated using SPSS and reported using a R-squared value. Line goodness-of-fit was assessed using an ANOVA linear or quadratic regression and reported using an F-value with a significance level of \( p < 0.001 \) used.

**Results**

**Acetabular Measurements**

There were no statistically significant differences in the baseline characteristics of the control hips and THA groups used to generate CT models (Table 1).

Table 3 describes the mathematic trend relationship of best fit between PR, the aforementioned hip angles and measurements of interest, with all trends calculated to be statistically significant \( (p < 0.001) \).

The acetabular anteversion distance (AAD) and lateral opening angle (LOA) demonstrated a linear and quadratic relationship with good correlation \( (R^2 = 0.923, R^2 = 0.710 \) respectively) in relation to pelvic rotation (Fig. 1, Graphs 1 and 3).

Combined change in area of prosthesis (AOP) demonstrated a moderate \( (R^2=0.449) \) linear correlation with pelvic rotation (Fig. 1, Graph 4).

This does not however account for different implant sizes. If separated into two analyses, prosthesis 1 and 2 yielded the following respectively, \( r^2 = 0.774, p < 0.001, F = 37.67, \) and \( r^2 = 0.875, p < 0.001, F = 77.27 \).

Change in acetabular inclination angle (AIA) and acetabular diameter (AD) both demonstrated weak correlations, with only approximately a third of the change variance explained by pelvic rotation using our model.

**Estimation of Rotation**

Change in PSSC and SPRR demonstrated very strong linear correlations with pelvic rotation respectively \( (R^2=0.970, R^2=0.953, p < 0.001, \) Graph 5 and 6).

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### Table 3 Effect of pelvic rotation on various measurements

| Acetabular measurement                          | Native THR | Trend | F value | \( R^2 \) | Sig. (\( p \)) | Graph |
|------------------------------------------------|------------|-------|---------|-----------|----------------|-------|
| Acetabular anteversion distance (AAD)           | \( n=3 \)  | \( n=0 \)linear | 394.65  | 0.923     | < 0.001        | 1     |
| Acetabular inclination angle (AIA)              | \( n=3 \)  | \( n=0 \)linear | 18.42   | 0.332     | < 0.001        | 2     |
| Acetabular inclination angle (AIA)              | \( n=3 \)  | \( n=2 \)linear | 20.89   | 0.359     | < 0.001        | 2     |
| Lateral opening angle (LOA)                     | \( n=3 \)  | \( n=0 \)quadratic | 60.75   | 0.771     | < 0.001        | 2     |
| Lateral opening angle (LOA)                     | \( n=3 \)  | \( n=2 \)quadratic | 75.98   | 0.710     | < 0.001        | 2     |
| Area of prosthesis (AOP)                       | \( n=0 \)  | \( n=2 \)linear | 19.56   | 0.449     | < 0.001        | 2     |
| Acetabular diameter (AD)                       | \( n=3 \)  | \( n=0 \)quadratic | 8.9     | 0.313     | < 0.001        | 2     |
| Estimation of rotation                         |            |       |         |           |                |       |
| PSSC                                           | \( n=3 \)  | \( n=0 \)linear | 884.39  | 0.960     | < 0.001        | 2     |
| SPRR                                           | \( n=3 \)  | \( n=2 \)linear | 2016.55 | 0.970     | < 0.001        | 5     |
| SPRR                                           | \( n=3 \)  | \( n=0 \)linear | 502.32  | 0.931     | < 0.001        | 2     |
| SPRR                                           | \( n=3 \)  | \( n=2 \)linear | 1284.32 | 0.953     | < 0.001        | 6     |
Discussion

This study was able to quantify the relationship between pelvic rotation and various acetabular angles from an AP radiograph. This was achieved using CT reconstructed images, where the degree of PR was manipulated and recorded with high precision. It has clinical significance as the AP radiograph remains the mainstay initial evaluation of pelvic anatomy for preoperative THA planning. Anatomical reconstruction of the joint is essential to achieve function, longevity and prevention of complications following surgery [1–7]. The study was able to comment on an acceptable degree of AP radiograph PR, as well as a simple method to quantify if this has been achieved.

For the purposes of this discussion in the context of interpretation in preoperative THA planning, trendlines of

![Graph 1: Acetabular anteversion distance](image1)

![Graph 2: Acetabular Inclination angle](image2)

![Graph 3: Lateral Opening angle](image3)

![Graph 4: Area of Prosthesis](image4)

![Graph 5: PSSC](image5)

![Graph 6: SPRR](image6)

Fig. 1 Graphs demonstrating effect of pelvic rotation on various angles. All observations made on left hips. Positive (+) rotation corresponds to pelvic rotation to the left (i.e. relative pelvic external rotation, ER), negative (−) rotation corresponds to pelvic rotation to the right (internal rotation, IR).
Graphs 1–6 (Fig. 1) were analysed and approximations were made between the angles of 0°–40° relative pelvic internal rotation (IR) and external rotation (ER). We recognise that there are numbers of different methods to assess acetabular anteversion in native and THA patients [21]. Our data suggest that the observed AAD (Graph 1) increases linearly by approximately 2°–3° for every 4° of pelvic rotation in either direction. It is clinically necessary to ensure an appropriately neutral pelvis to avoid falsely interpreting excessive anteversion. We suggest that up to 20° of PR will lead to a safe estimation of AAD. Since the originally obtaining our data, findings from Yun et al. support our results to suggest that PR effects acetabular anteversion [22, 23]. However, their studies utilised a different method of determining acetabular anteversion, they were not able to precisely control the extent of PR, nor isolate any PR from pelvic tilt, a variable which is known to affect acetabular angles.

In contrast, the lateral opening angle (LOA) tends to increase linearly from relative pelvic IR to ER by approximately 1° for every 4° of PR. Rojas et al. [24] found that an altered pre-operative Sharp’s angle (methodologically similar to LOA [25]) was associated with cup malpositioning (OR 2.51, \( p = 0.02 \)). It is therefore imperative to ensure minimal PR and therefore accurate preoperative LOA to avoid potential cup mal-positioning and therefore potentially poor THA outcomes. There is a sparsity of literature reporting the effect of PR on LOA; however, our results are consistent with one study’s conclusion that PR increases the error of acetabular index in 3-month-olds with developmental dysplasia of the hip [26]. A study from Tannast et al. [19] that applied a similar method using CT imaging demonstrated methodological accuracy with good reproducibility and reliability. It also revealed Sharp’s angle did not have a clinically significant change between neutral to 12° (bilaterally), however, their experiment did not report beyond 12° of PR. Clinically, we suggest that up to 20° of PR will lead to minimal impact on the final measurement of LOA.

The AOP tends to increase linearly from relative pelvic ER to IR by approximately 1 cm² for every 4° of PR. The AOP for the two different implant sizes in in Graph 4 must be analysed separately to be clinically meaningful, yielding good linear correlation with PR. This has the potential clinical implication that a relative pelvic internal rotation can result in an under estimation of post-operative acetabular prosthetic coverage and therefore implant size choice. Likewise, PR of less than 20° is unlikely to pose a significant negative impact on AOP estimation. It is also recommended that future analyses group datapoints for similar implant sizes to reduce unnecessary variation.

Taking into consideration that both AIA and AD demonstrated a weak correlation with PR, the AIA tends to increase linearly from relative pelvic ER to IR by approximately 1° for every 5° of PR. AD tended to follow a quadratic trendline, where both IR and ER of the pelvis reduced observed AD by approximately 1.5 mm per 10° of rotation. A study by Ghostine et al. (2016) [27] investigating 3-D reconstructions from bi-planar radiographs also reported that AIA and acetabular anteversion were minimally affected by PR from neutral to 20° in comparison with other hip parameters, thereby supporting our results. The clinical applicability of our AIA and AD data is however tenuous.

As previously discussed, incorrect acetabular prosthetic cup positioning is known to be associated with poor clinical outcomes, such as impingement, instability or prosthetic failure [1–7]. It is therefore important to determine an acceptable degree to PR that will not significantly bias preoperative planning. Synthesising results from this proof-of-concept study, PR of more than 20° can produce unreliable acetabular angles and measurements, leading to increased risk of incorrect prosthesis placement. It is therefore imperative to ensure a safe amount of PR on AP radiograph.

### Estimation of Rotation

In this study, actual pelvic rotation determined by CT can be estimated on AP radiograph using the horizontal distance between the pubic symphysis and middle of the sacrococcygeal joint (PSSC) and the horizontal distance between the two anterior superior iliac spines (HASIS). The results show a near-perfect correlation between PSSC and PR, giving a clear indication to the extent of PR on an AP radiograph. These results are comparable to a previous study [20] that employed similar methodology on 20 cadavers. Using the trendline from Graph 5, a PSSC of less than 10 mm is expected at 0° of pelvic rotation, with an increase of approximately 20 mm for every 10° of PR in either direction.

It can be argued however that these measurements are subject to individual patient anthropometry, gender, size, radiographic technique and analysis software; therefore, a more patient-specific method was investigated. Using a novel ratio, the SPRR, patient factors and imaging techniques were expected to have less overall impact. Using Graph 6, at neutral pelvic rotation, the SPRR is shown to be less than 1. As PR increases in either direction, PSSC (measured in mm) increases and HASIS (measured in cm) decreases, therefore the ratio increases. Analysing preliminary data used in this study, an SPRR greater than 2.0 is therefore likely associated with radiograph pelvic rotation of more than 20°. It would therefore seem appropriate for this value to be employed as a safe cut-off for PR tolerance.

### Limitations

This novel proof-of-concept study does have some methodological limitation, including a limited sample size of pelvises, single observer and unilateral hip measurements.
It would therefore be questionable to generalise the exact values to a particular age bracket, gender or specific diagnostic indication for THA. The 3-D pelvis models generated we used were based on real human pelvises, therefore are subject to individual anatomical differences. The goal of this study however was not to necessarily report the absolute acetalubar angles, but rather to demonstrate the effect of PR on these values. We reasoned that pelvises of differing anatomical structure would have similar degrees of changes due to PR, regardless of the absolute acetalubar angle measurement. Similarly, the age of the data is unlikely to impact the observed changes in measured acetalubar angles. Despite these limitations therefore, the trendlines discussed demonstrated acceptable goodness-of-fit and clinically useful data for, AAD, LOA, estimation of rotation using PSSC and SPRR. Based on these outcomes, we were able to provide an estimate the potential acceptableness of PR from an AP pelvis radiograph.

Conclusion

Pelvic rotation can significantly impact on the perceived acetalubar angles observed on an AP pelvic radiograph, which can in turn result in poor prosthetic placement and potentially subsequent poorer long-term clinical outcomes. Data from our initial study indicate that PR of less than 20° is unlikely to have a clinical impact of preoperative measures and therefore serve as a guide for clinical application.

We propose that our new and novel ratio of SPRR of more than 2.0 may serve as a simple and reproducible surrogate for measured PR of > 20°.

Author contributions EL: contributed to this research (1) conception and design, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be published, and (4) agree to be accountable for all aspects of the work if questions arise related to its accuracy or integrity. LWY: contributed to this research (1) conception and design, or acquisition of data, or analysis and interpretation of data, (2) drafting the article or revising it critically for important intellectual content, (3) final approval of the version to be published, and (4) agree to be accountable for all aspects of the work if questions arise related to its accuracy or integrity.

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