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徐, 明剣

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Original article

Proximal femoral morphology after transtrochanteric posterior rotational osteotomy for osteonecrosis of the femoral head: A three-dimensional simulation study

Mingjian Xu, Goro Motomura*, Satoshi Ikemura, Ryosuke Yamaguchi, Takeshi Utsunomiya, Shoji Baba, Koichiro Kawano, Yasuharu Nakashima

Department of orthopaedic surgery, Graduate school of medical sciences, Kyushu University, 3-1-1, Maidashi, Higashi-ku, 812-8582 Fukuoka, Japan

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ABSTRACT

Background: Transtrochanteric posterior rotational osteotomy (PRO) is one of the joint-preserving surgeries for osteonecrosis of the femoral head. In general, postoperative femoral neck-shaft varus realignment is planned to obtain a sufficient intact articular surface of the femoral head in the weight-bearing portion. Unlike anterior rotational osteotomy, PRO allows for more than 90° rotation of the femoral head, resulting in more complicated morphology. However, little is known about the potential risk of postoperative femoral retroversion after PRO. This simulation study aims: 1) to assess whether postoperative femoral neck-shaft varus realignment can coexist with preserved femoral anteversion after PRO, 2) and whether postoperative proximal femoral morphology could be predicted with approximation equations.

Hypothesis: High degree (>90°) PRO is favourable for femoral neck-shaft varus realignment, but unfavourable for maintaining postoperative femoral anteversion.

Materials and methods: PRO was simulated by using CT data from 10 hips in 10 healthy volunteers. During simulation, the intertrochanteric osteotomy plane was determined three-dimensionally based on anteroposterior-view line (the osteotomy line on anteroposterior view) and lateral-view line (the osteotomy line on lateral view). By changing either the angle of anteroposterior-view line or lateral-view line, we simulated 90°, 110°, 130° and 150° PRO. To clarify the effects of various posterior rotation angles on postoperative proximal femoral morphology, we made simplified PRO models through changing only the posterior rotation angle.

Results: In the 90°, 110°, 130° and 150° PRO models, the vertically inclined angle of anteroposterior-view line showed a significant positive correlation with femoral neck-shaft varus realignment (90° PRO, $r=0.90$; 110° PRO, $r=0.95$; 130° PRO, $r=0.97$; 150° PRO, $r=0.99$), while a significant negative correlation with postoperative femoral anteversion angle (90° PRO, $r=-0.97$; 110° PRO, $r=-0.95$; 130° PRO, $r=-0.92$; 150° PRO, $r=-0.7$). Likewise, the posteriorly tilted angle of lateral-view line showed a significant negative correlation with both femoral neck-shaft varus realignment (90° PRO, $r=-0.81$; 110° PRO, $r=-0.81$; 130° PRO, $r=-0.79$; 150° PRO, $r=-0.72$) and postoperative femoral anteversion angle (90° PRO, $r=-0.90$; 110° PRO, $r=-0.89$; 130° PRO, $r=-0.92$; 150° PRO, $r=-0.88$). In the simplified PRO models, the posterior rotation angle showed a significant positive correlation with femoral neck-shaft varus realignment ($r=0.33$), while a significant negative correlation with postoperative femoral anteversion angle ($r=-0.76$). The approximation equations for predicting the proximal femoral morphology after PRO were validated.

Discussions: It was confirmed that high-degree PRO (>90°) is favourable for femoral neck-shaft varus realignment, but works against preserving femoral anteversion. With the approximation equations developed in the current study, surgeons could examine the feasibility of PRO based on postoperative femoral anteversion. In terms of hip joint function and subsequent total hip arthroplasty, excessive deformities including femoral retroversion and severe varus deformity could be avoided.

Level of evidence: IV; case series without control group.

* Corresponding author.
E-mail address: goromoto@ortho.med.kyushu-u.ac.jp (G. Motomura).

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1. Introduction

Transtrochanteric posterior rotational osteotomy (PRO) has been reported to be one of the joint-preserving surgeries for osteonecrosis of the femoral head [1–7]. The postoperative intact ratio, defined as a ratio of the intact articular surface of the femoral head to the weight-bearing area of the acetabulum on a postoperative anteroposterior radiograph, should be at least 36.8% to avoid progression of collapse and joint space narrowing after transtrochanteric osteotomy surgery [8]. Therefore, intentional femoral neck-shaft varus realignment is often designed during PRO by changing the intertrochanteric osteotomy plane.

In contrast to transtrochanteric anterior rotational osteotomy (ARO) [9,10], PRO allows for more than 90° rotation of the femoral head without kinking it's feeding vessels. The upper limit is approximately 140° to 150° [6]. Due to the existence of native femoral anteversion, it is difficult to understand the effects of intertrochanteric osteotomy plane on the postoperative proximal femoral morphology especially after PRO > 90°. Although a previous PRO study based on radiographic images showed an association between various posterior rotation angles and femoral neck-shaft varus realignment [3], little is known about the risk of postoperative femoral retroversion. Since femoral retroversion is reported to be associated with osteoarthritis, hip pain, and femoroacetabular impingement [11,12], femoral retroversion after PRO should be avoided as much as possible.

To clarify this issue and to forecast this potential femoral deformity, we performed a three-dimensional CT-based simulation study of PRO:

- to evaluate whether femoral neck-shaft varus realignment could coexist with preserved femoral anteversion;
- and whether postoperative proximal femoral morphology could be predicted with approximation equations.

We hypothesised that high degree (> 90°) PRO is favourable for femoral neck-shaft varus realignment, but unfavourable for maintaining postoperative femoral anteversion.

2. Materials and methods

2.1. Subjects

CT data were obtained from 10 healthy volunteers (8 males, 2 females) without any history of hip surgery. The mean age of volunteers was 36 years (32–39 years).

2.2. CT Imaging

All CT imaging (Aquilion; Toshiba, Tochigi, Japan) were performed with volunteers in the supine position at 2-mm intervals from anterior superior iliac spine to knee. The mean radiation exposure for volunteers was 820.4 mGy cm (range, 794.6–927.6 mGy cm). Three-dimensional simulation of PRO was performed using the Zed Osteotomy program (LEXI, Tokyo, Japan) with CT data in DICOM format.

2.3. Definition of parameters

The definition of femoral neck-shaft angle and femoral anteversion angle was in accordance with a previously study of ARO [10]. Postoperative femoral neck-shaft varus angle was calculated by preoperative femoral neck-shaft angle minus postoperative femoral neck-shaft angle.

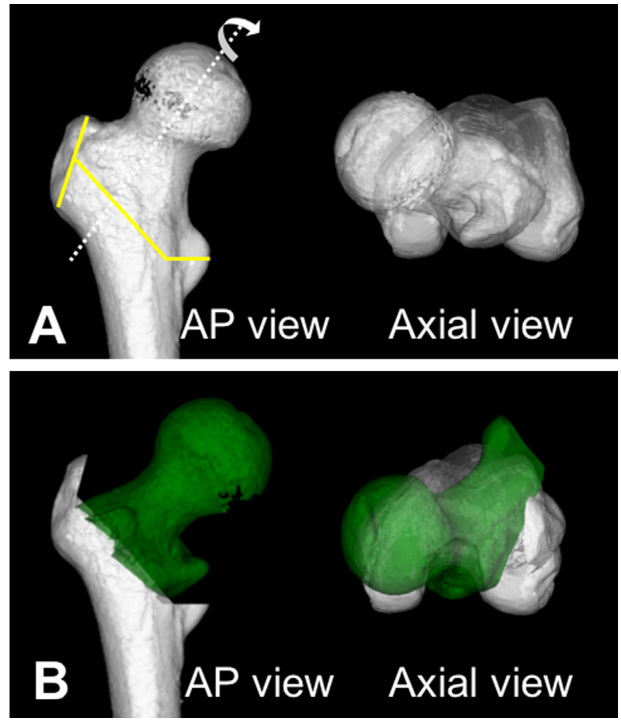

Fig. 1. A. During simulation of participant 1, after three osteotomy processes (yellow lines), the femoral head was posteriorly rotated (white arrow), B. And the proximal femoral morphology (green area) was changed after rotation.

2.4. PRO simulation

PRO was simulated in the following order (Fig. 1):

- osteotomy of greater trochanter;
- intertrochanteric osteotomy;
- osteotomy at lesser trochanter;
- posterior rotation of femoral head.

The simulation was performed on tabletop coordinate system, in which the table plane includes the posterior aspect of femoral condyles and the most prominent posterior point of greater trochanter. The intertrochanteric osteotomy plane was defined three-dimensionally by anteroposterior-view line (the osteotomy line on anteroposterior view) (Fig. 2A) and lateral-view line (the osteotomy line made through the cut surface of greater trochanter on lateral view) (Fig. 2B). By changing either the vertically inclined angle of anteroposterior-view line in 5° increments from −10° to 15° or the posteriorly tilted angle of lateral-view line in 5° increments from −10° to 10° or both, we performed 90°, 110°, 130°, and 150° PRO, with altogether 1200 hip models produced. In addition, by fixing both anteroposterior-view line and lateral-view line in basic positions and changing the posterior rotation angle in 10° increments from 60° to 150°, another 100 simplified hip models were produced. The femoral neck-shaft angle and femoral anteversion angle in each hip model were measured before and after PRO simulation (Fig. 1).

2.5. Statistical analysis

Shapiro–Wilk test was performed to evaluate the distribution of age, preoperative femoral neck-shaft angle and preoperative femoral anteversion angle.

In the 90°, 110°, 130° and 150° PRO models, with lateral-view line fixed in −5°, which is a preferred angle in practical surgery,

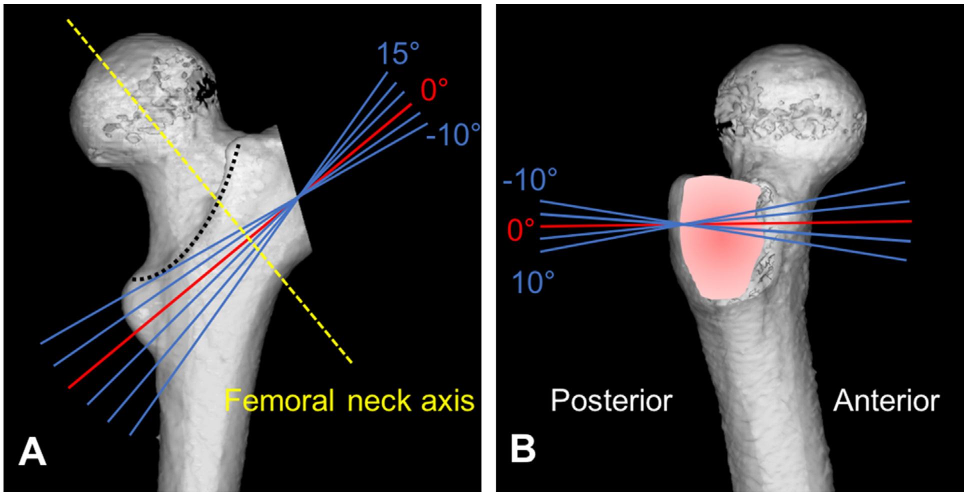

Fig. 2. A. The basic position of anteroposterior-view line (red line) was defined as perpendicular to femoral neck axis (yellow dashed line) and 1 cm distal to the intertrochanteric crest (black dashed line) on anteroposterior view. B. The basic position of lateral-view line (red line) was defined as perpendicular to the table plane. The pink ellipsoid indicates the cut surface of greater trochanter.

Table 1
Preoperative femoral neck-shaft angle and preoperative femoral anteversion angle.

Participant	Age (years)/sex	Femoral neck-shaft angle (°)	Femoral anteversion angle (°)
1	36/Male	131	7.8
2	38/Male	123.6	6.1
3	37/Male	121.2	11.3
4	36/Male	131	28.8
5	37/Male	128.6	22.5
6	39/Male	128.3	22.5
7	36/Male	119.4	8.7
8	36/Male	133.3	15.1
9	32/Female	123.7	16.6
10	33/Female	122.3	19.4

the relationship of vertically inclined angle of anteroposterior-view line with postoperative proximal femoral morphology, including femoral neck-shaft varus angle and femoral anteversion angle, was assessed using Pearson's correlation coefficients. Similarly, with anteroposterior-view line fixed in basic position, the relationship of posteriorly tilted angle of lateral-view line with postoperative proximal femoral morphology was assessed.

Multiple regression analysis was performed for postoperative femoral neck-shaft varus angle and postoperative femoral anteversion angle. The explanatory variables included vertically inclined angle of anteroposterior-view line, posteriorly tilted angle of lateral-view line, and preoperative femoral anteversion angle. Interaction terms were added. Variables with statistical significance ($p < 0.05$) and a parameter estimate of > 0.1 were included into the approximation equations.

In the simplified PRO models, the relationship of posterior rotation angle with postoperative proximal femoral morphology was assessed using the Pearson's correlation coefficients. All statistical analyses were performed using JMP (version 13; SAS Institute, Cary, NC).

3. Results

Intra-observer reliability for the measurements (pre- and postoperative femoral neck-shaft angle, pre- and postoperative femoral anteversion angle) was good (0.99, 0.98, 0.99 and 0.97, respectively). Inter-observer reliability for the measurements was also good (0.95, 0.99, 0.94 and 0.96, respectively).

The mean preoperative femoral neck-shaft angle and femoral anteversion angle were 126.2 ± 4.6° (119.4–133.3°) and 15.9 ± 7.1° (6.1–28.8°), respectively (Table 1). Shapiro–Wilk test showed normal distribution in age ($W = 0.90$, $p = 0.22$), preoperative femoral neck-shaft angle ($W = 0.93$, $p = 0.47$) and preoperative femoral anteversion angle ($W = 0.95$, $p = 0.71$).

In the 90°, 110°, 130° and 150° PRO models, the increase of vertically inclined angle of anteroposterior-view line induced femoral neck-shaft varus realignment while there was a decrease of femoral anteversion angle (Fig. 3). In the same manner, the decrease of posteriorly tilted angle of lateral-view line induced femoral neck-shaft varus realignment and increase of femoral anteversion angle (Fig. 4). In addition, the vertically inclined angle of anteroposterior-view line showed a significant positive correlation with femoral neck-shaft varus realignment while a significant negative correlation with postoperative femoral anteversion angle. Likewise, the posteriorly tilted angle of lateral-view line showed a significant negative correlation with both femoral neck-shaft varus realignment and postoperative femoral anteversion angle (Table 2). Multiple regression analyses demonstrated that both postoperative femoral neck-shaft varus angle and postoperative femoral anteversion angle were determined by vertically inclined angle of anteroposterior-view line, posteriorly tilted angle of lateral-view line, and preoperative femoral anteversion angle (Tables 3 and 4). The approximation equations are showed in Table 5.

In the simplified PRO models, the increase of posterior rotation angle from 90° to 150° induced femoral neck-shaft varus realignment while there was a decrease of femoral anteversion angle (Fig. 5). In addition, the increase of posterior rotation angle showed a positive correlation with femoral neck-shaft varus realignment ($r = 0.33$, $p = 0.0009$) while a negative correlation with postoperative femoral anteversion angle ($r = -0.84$, $p < 0.0001$).

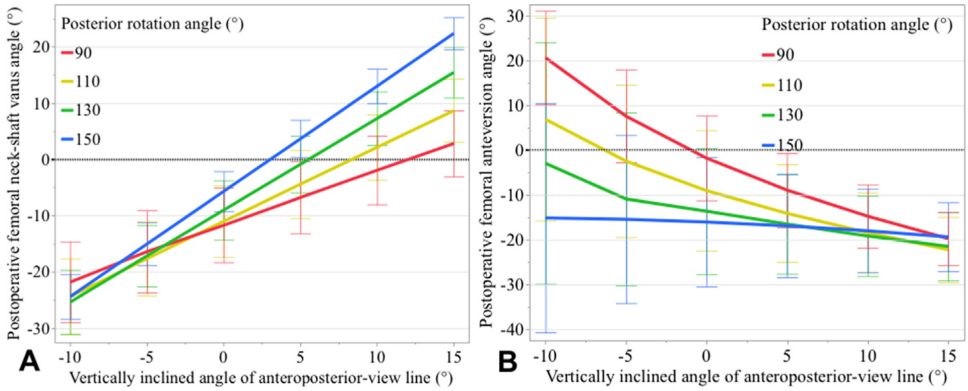

Fig. 3. A. With lateral-view line fixed in −5° position, as the vertically inclined angle of anteroposterior-view line increased, the postoperative femoral neck-shaft varus angle increased (mean ± SD). B. While the postoperative femoral anteversion angle decreased (mean ± SD).

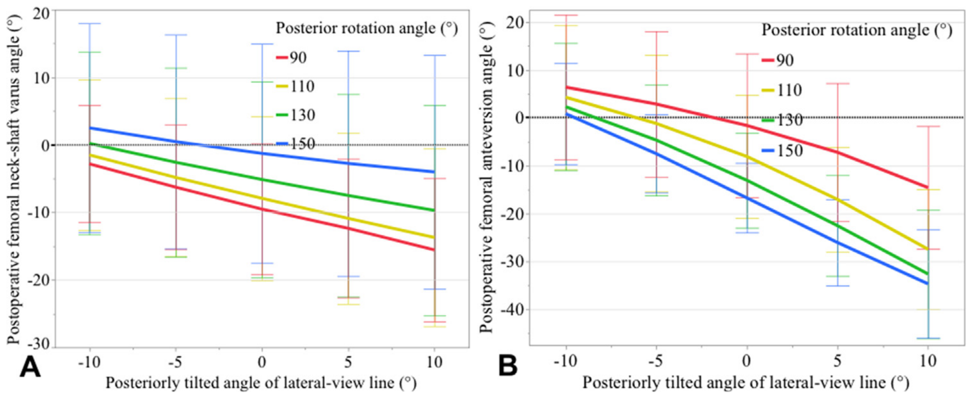

Fig. 4. A. With anteroposterior-view line fixed in basic position, as the posteriorly tilted angle of lateral-view line decreased, both the postoperative femoral neck-shaft varus angle (mean ± SD). B. And femoral anteversion angle (mean ± SD) increased.

Table 2
Pearson's correlation coefficients for 90°, 110°, 130° and 150° PRO.

Dependent variable	Independent variable	Group							
		90° PRO		110° PRO		130° PRO		150° PRO	
		r	*p*-value	*r*	*p*-value	*r*	*p*-value	*r*	*p*-value
Postoperative femoral neck-shaft varus angle	Vertically inclined angle of anteroposterior-view line	0.90	< 0.0001	0.95	< 0.0001	0.97	< 0.0001	0.99	< 0.0001
	Posteriorly tilted angle of lateral-view line	−0.81	< 0.0001	−0.81	< 0.0001	−0.79	< 0.0001	−0.72	< 0.0001
Postoperative femoral anteversion angle	Vertically inclined angle anteroposterior-view line	−0.97	< 0.0001	−0.95	< 0.0001	−0.92	< 0.0001	−0.7	< 0.0001
	Posteriorly tilted angle of lateral-view line	−0.90	< 0.0001	−0.89	< 0.0001	−0.92	< 0.0001	−0.88	< 0.0001

Table 3
Multiple regression analysis for postoperative femoral neck-shaft varus angle.

Parameter	Group							
	90° PRO		110° PRO		130° PRO		150° PRO	
	Parameter estimate	*p*-value	Parameter estimate	*p*-value	Parameter estimate	*p*-value	Parameter estimate	*p*-value
Intercept	−2.12	< 0.0001	−2.59	< 0.0001	0.24	0.0045	0.48	0.0002
Vertically inclined angle of anteroposterior-view line	0.98	< 0.0001	1.32	< 0.0001	1.63	< 0.0001	1.87	< 0.0001
Posteriorly tilted angle of lateral-view line	−0.63	< 0.0001	−0.61	< 0.0001	−0.49	< 0.0001	−0.33	< 0.0001
Preoperative femoral anteversion angle	−0.61	< 0.0001	−0.53	< 0.0001	−0.58	< 0.0001	−0.38	< 0.0001

Table 4
Multiple regression analysis for postoperative femoral anteversion angle.

Parameter	Group							
	90° PRO		110° PRO		130° PRO		150° PRO	
	Parameter estimate	*p*-value	Parameter estimate	*p*-value	Parameter estimate	*p*-value	Parameter estimate	*p*-value
Intercept	3.0	< 0.0001	4.49	< 0.0001	1.72	0.0208	0.26	0.61
Vertically inclined angle of anteroposterior-view line	−1.58	< 0.0001	−1.13	< 0.0001	−0.65	< 0.0001	−0.17	< 0.0001
Posteriorly tilted angle of lateral-view line	−1.04	< 0.0001	−1.59	< 0.0001	−1.78	< 0.0001	−1.79	< 0.0001
Preoperative femoral anteversion angle	−0.12	0.001	−0.73	< 0.0001	−0.9	< 0.0001	−1.04	< 0.0001

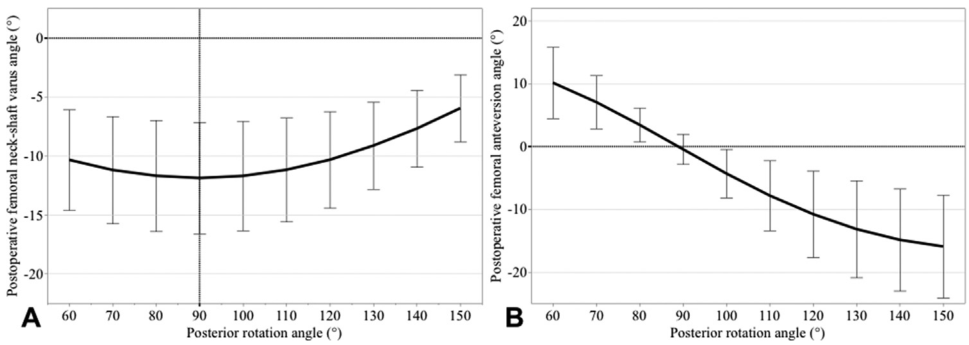

Fig. 5. A. With both anteroposterior-view line and lateral-view line fixed in basic position, as the posterior rotation angle increased from 90° to 150°, the postoperative femoral neck-shaft varus angle increased (mean ± SD). B. As the posterior rotation angle increased from 60° to 150°, the postoperative femoral anteversion angle decreased (mean ± SD).

Table 5
Approximation equations for postoperative femoral neck-shaft varus angle and postoperative femoral anteversion angle.

Group	Approximation equation	Adjusted R^2 value
90° PRO	$P_V \approx -2.12 + 0.98 \times A - 0.63 \times L - 0.61 \times F$	0.97
	$P_A \approx 3.0 - 1.58 \times A - 1.04 \times L - 0.12 \times F$	0.92
110° PRO	$P_V \approx -2.59 + 1.32 \times A - 0.61 \times L - 0.53 \times F$	0.97
	$P_A \approx 4.49 - 1.13 \times A - 1.59 \times L - 0.73 \times F$	0.92
130° PRO	$P_V \approx 0.24 + 1.63 \times A - 0.49 \times L - 0.58 \times F$	1
	$P_A \approx 1.72 - 0.65 \times A - 1.78 \times L - 0.9 \times F$	0.93
150° PRO	$P_V \approx 0.48 + 1.87 \times A - 0.33 \times L - 0.38 \times F$	1
	$P_A \approx - 0.17 \times A - 1.79 \times L - 1.04 \times F$	0.96

P_V = postoperative femoral neck-shaft varus angle; P_A = postoperative femoral anteversion angle; A = vertically inclined angle of anteroposterior-view line; L = posteriorly tilted angle of lateral-view line; F = preoperative femoral anteversion angle.

4. Discussion

To date, the preoperative planning for PRO has mainly focused on obtaining a sufficient postoperative intact ratio. Less attention has been paid to the risk of postoperative femoral retroversion. Postoperative proximal femoral morphology after PRO is difficult to predict, especially for PRO with more than 90° of posterior rotation. The current study confirmed that high-degree (> 90°) PRO is favourable for femoral neck-shaft varus realignment but works against maintaining postoperative femoral anteversion. As a solution, the approximation equations developed here can be used in preoperative planning to examine the feasibility of PRO. During PRO, both required varus angle, and posterior rotation angle is necessarily determined by the location and extent of the anterior intact area of the femoral head. With use of the approximation equations developed in the current study, the surgeon could examine the feasibility of PRO based on postoperative femoral anteversion. If there is no available combination of osteotomy lines leading to acceptable postoperative femoral anteversion, the surgeon could reconsider the indication of PRO before surgery.

Few investigations have focused on the postoperative femoral anteversion angle, including studies with simulated femoral osteotomy [13–18]. Since the femoral retroversion is reported to be associated with osteoarthritis, hip pain, and femoroacetabular impingement [11,12], a femoral retroversion after PRO should be avoided. Our results demonstrated that the decrease of posteriorly tilted angle of lateral-view line is advantageous for obtaining varus realignment and avoiding femoral retroversion (Fig. 4). On the other hand, the increase of vertically inclined angle of anteroposterior-view line leads not only to varus realignment, but also to increased risk of femoral retroversion (Fig. 3). These findings suggest that lateral-view line should be prioritised over anteroposterior-view line to avoid femoral retroversion.

High-degree (> 90°) PRO is reportedly associated with varus realignment in a two-dimensional radiographic study [4]. The current three-dimensional simulation study showed that high-degree PRO leads to a moderate varus realignment ($r = 0.33$, $p = 0.0009$), but a strong risk of femoral retroversion ($r = -0.84$, $p < 0.0001$). However, it is difficult to reduce the risk of retroversion caused by high-degree PRO during surgery. As a solution, the approximation equations developed here can be used in preoperative planning to examine the feasibility of PRO.

During ARO, preoperative femoral anteversion is advantageous to obtain a varus realignment [10], while the current study indicates that preoperative femoral anteversion is disadvantageous to obtain a varus realignment during PRO (Table 5). This result also supports Sugioka's theory [6]. In addition, femoral anteversion after ARO depends only on the intertrochanteric osteotomy plane [10], while femoral anteversion after PRO is influenced not only by intertrochanteric osteotomy plane, but also preoperative femoral anteversion (Table 5). On the contrary of ARO, a high preoperative femoral anteversion angle seems to be a risk factor during PRO. Detailed comparison of ARO and PRO was shown in Table 6.

Table 6
Effects of different parameters on postoperative proximal femoral morphology during ARO and PRO.

Parameter	ARO		PRO	
	Postoperative femoral neck-shaft angle	Postoperative femoral anteversion	Postoperative femoral neck-shaft angle	Postoperative femoral anteversion
Increase of vertically inclined angle of anteroposterior-view line	Varus	Anteversion	Varus	Retroversion
Increase of posteriorly tilted angle of lateral-view line	Varus	Retroversion	Valgus	Retroversion
Preoperative femoral anteversion angle	Varus	No effect	Valgus	Retroversion
High degree (> 90°) femoral head rotation	/	/	Varus	Retroversion

This study had several limitations. The first was the small sample size. However, the adjusted R^2 values shown in Table 5 were all close or equal to 1, indicating that the number of subjects was enough to produce almost perfect approximation equations. Secondly, the CT data was obtained from healthy femoral heads rather than collapsed femoral heads of osteonecrosis. However, since we used 4 points at the uncollapsed femoral head surface to obtain the best fit sphere of the femoral head, the parameter measurements do not vary between healthy and osteonecrotic femoral heads. Thirdly, it is difficult for surgeons to control the intraoperative osteotomy line as accurately as the simulation software. A surgical navigation system would help to make the procedures more accurate.

5. Conclusion

The current study suggests that, by using the approximation equations developed from our results, high-degree (> 90°) PRO could be used as a supplement for the femoral neck-shaft varus realignment and the postoperative femoral anteversion could also be preserved. In terms of hip joint function and subsequent total hip arthroplasty [19], excessive deformities including femoral retroversion and severe varus deformity could be avoided.

Disclosure of interest

The authors declare that they have no competing interest.

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Authors' contributions

Mingjian Xu designed the study, contributed to analysis of data, and wrote the initial manuscript. Goro Motomura contributed to analysis and interpretation of data, and assisted in the preparation of the manuscript. All other authors have contributed to data collection and interpretation, and critically reviewed the manuscript. All authors approved the final version of the manuscript, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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