The influence of hip rotation on femoral offset in plain radiographs

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Submitted 2013-12-08. Accepted 14-04-01

Background and purpose — Adequate restoration of femoral offset (FO) is critical for successful outcome after hip arthroplasty or fixation of hip fracture. Previous studies have identified that hip rotation influences the projected femoral offset (FO_P) on plain anteroposterior (AP) radiographs, but the precise effect of rotation is unknown.

Patients and methods — We developed a novel method of assessing rotation-corrected femoral offset (FO_{RC}), tested its clinical application in 222 AP hip radiographs following proximal femoral nailing, and validated it in 25 cases with corresponding computed tomography (CT) scans.

Results — The mean FO_{RC} was 57 (29–93) mm, which differed significantly ($p < 0.001$) from the mean FO_P 49 (22–65) mm and from the mean femoral offset determined by the standard method: 49 (23–66) mm. FO_{RC} correlated closely with femoral offset assessed by CT (FO_{CT}); the Spearman correlation coefficient was 0.94 (95% CI: 0.88–0.97). The intraclass correlation coefficient for the assessment of FO_{RC} by AP hip radiographs correlating the repeated measurements of 1 observer and of 2 independent blinded observers was 1.0 and 1.0, respectively.

Interpretation — Hip rotation affects the FO_P on plain AP radiographs of the hip in a predictable way and should be adequately accounted for.

Meticulous reconstruction of the static and dynamic components of the biomechanical properties of the joint is important (Girard et al. 2006). Previous reports have emphasized the importance of restoring the femoral offset (FO) to achieve optimal postoperative joint function (Bourne and Rorabeck 2002). Furthermore, restoration of femoral offset plays a vital role in ensuring a good clinical outcome after fixation of proximal femoral fractures (Eijer et al. 2001, Paul et al. 2012). Adequate preoperative planning and precise postoperative assessment of femoral offset depend on the availability of highly standardized radiographic images of the hip joint (Merle et al. 2012). Inadequate hip rotation (HR) has been reported to result in substantial misinterpretation of the femoral offset on plain anteroposterior (AP) radiographs of the hip (Meyer and Kotecha 2008). However, the exact relationship between hip rotation and the projected femoral offset (FO_P) is not known.

List of abbreviations

AP	anteroposterior
CCD	caput-collum-diaphyseal angle
CCD_I	caput-collum-diaphyseal angle of the implant
CCD_P	projected caput-collum-diaphyseal angle
CF	calibration factor
CI	confidence interval
CN	center of femoral nail
CT	computed tomography
FH	femoral head
FO	femoral offset
FO_{cos}	cosine-function-dependent femoral offset
FO_{CT}	computed tomography-assessed femoral offset
FO_{LS}	lag screw-corrected femoral offset
FO_P	projected femoral offset
FO_{RC}	rotation-corrected femoral offset
HR	hip rotation
ICC	intraclass correlation coefficient
LS	lag screw
LS_P	projected lag screw
ND	nail diameter
ND_P	projected nail diameter
RCF	rotation-correction factor as assessed by the tangent function
RCF_{cos}	rotation-correction factor as assessed by the cosine function
γP	projected gamma angle of the implant
γI	gamma angle of the implant

DOI 10.3109/17453674.2014.931196

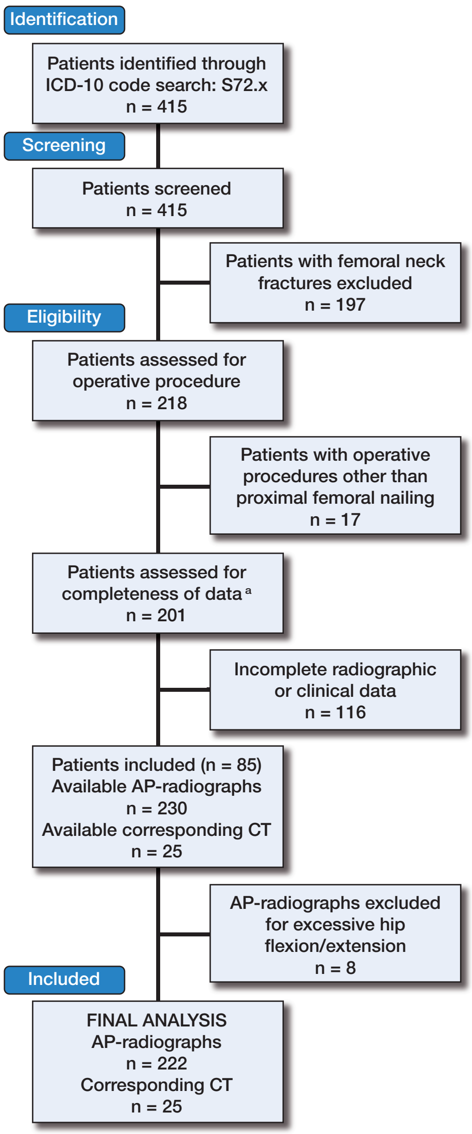

Figure 1. Flow chart for inclusion and exclusion of patients, anteroposterior radiographs, and computed tomography of the hip.

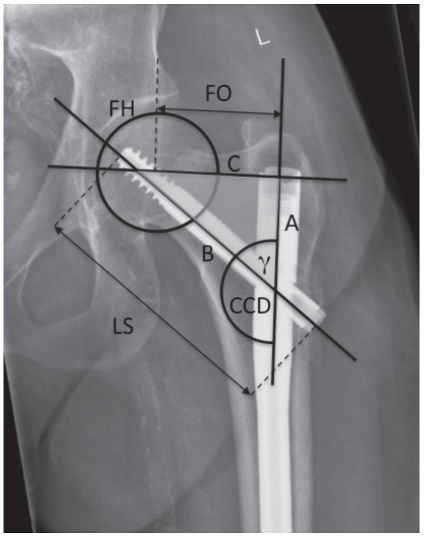

Figure 2. A pertrochanteric fracture treated with proximal femoral nailing. Anatomic and implant measurements are shown. A – proximal nail shaft axis, B – leg screw axis, C – perpendicular line from the center of rotation of the femoral head to the long axis of the proximal part of the femoral nail shaft, FH – femoral head, FO – femoral offset, LS – leg screw, CCD_P – projected caput-collum-diaphyseal angle, γP – projected gamma angle of the implant.

We built a mathematical model to explain correlation between hip rotation and the FO_P on plain AP hip radiographs. A new method for assessment of rotation-corrected femoral offset (FO_{RC}) after proximal femoral nailing was developed and validated using computed tomography (CT) scans.

Patients and methods

We enrolled 85 patients with proximal femoral fractures who underwent intramedullary nailing of the proximal femur at our institution between January 2011 and December 2012 (Figure 1). The same type of implant with a nail length of 21.5 cm, nail diameter of 11.5 mm, caput-collum-diaphyseal (CCD) angle of 130°, and a lag screw diameter of 10.5 mm (Zimmer Natural Nail System, Cephalo-medullary Nail; Zimmer Inc., Warsaw, IN) was used in all patients according to the manufacturer's instructions, albeit with varying lag screw length (85–130 mm). Intraoperative radiographs were obtained with a Siemens Siremobil compact GE OEC 9900 C-arm (Siemens Medical Solutions, Erlangen, Germany) with the focus at 1,000 mm. For intraoperative AP radiographs, hip rotation was minimized and the axial view confirmed the centered position of the lag screw in the femoral neck. Postoperatively, standardized AP radiographs of the hip (n = 222) with 15° of internal rotation of the leg and axial plains were obtained in the supine position with a tube-to-film distance of 1,150 mm. Radiographs with considerable hip flexion or extension were excluded. For validation, 25 AP radiographs with corresponding CT scans of the 85 patients included were analyzed (Figure 1). Patients were positioned supine in a Siemens Somatom scanner; scans were acquired using a standardized protocol. Radiographs and CT scans were stored in a picture-archiving and communication system, and analyzed using proprietary software (IMPAX and IMPAX EE, respectively; AGFA HealthCare GmbH, Bonn, Germany).

Measurement of femoral offset

Femoral offset was defined as the perpendicular distance from the center of rotation of the femoral head to the long axis of the proximal part of the femoral nail shaft (Merle et al. 2012) so that the femoral offset, the femoral nail shaft axis, and the lag screw axis created a right-angled triangle (Figure 2). According to Pythagoras' theorem and basic trigonometry, the

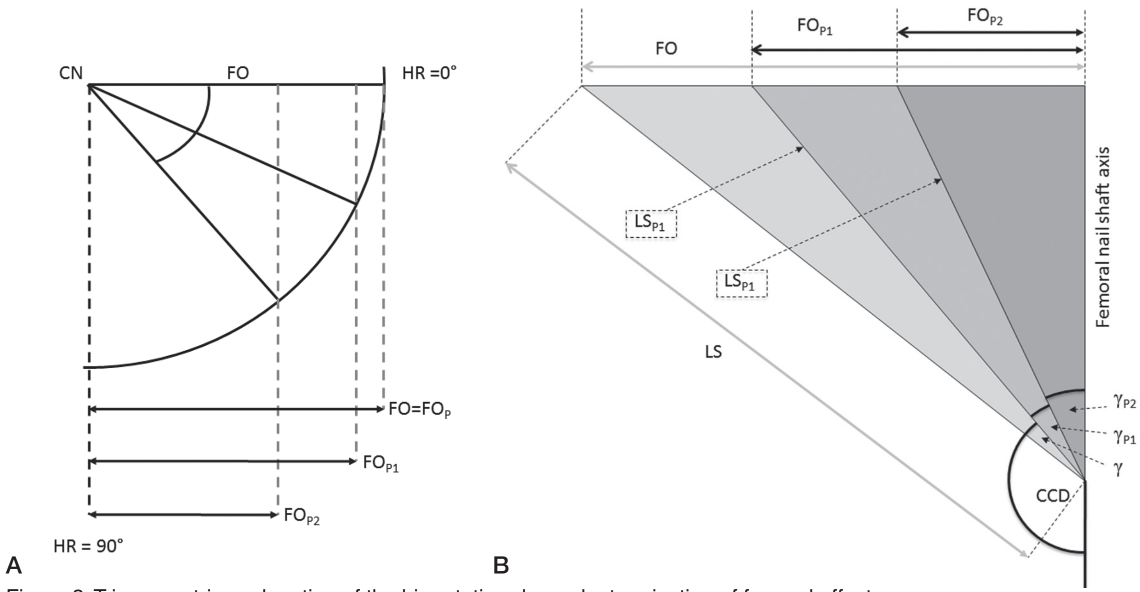

Figure 3. Trigonometric explanation of the hip rotation-dependent projection of femoral offset.
A. Schematic axial (transversal) view of the femoral offset (FO) for varying degrees of hip rotation (HR) around the center of the femoral nail (CN). Projected femoral offset (FO_P) depends on hip rotation and is explained by the cosine function of HR: FO = FO_P/ cos (HR).
B. Schematic coronal view (anteroposterior) of the triangle composed by FO, femoral nail shaft axis, and lag screw axis for varying degrees of hip rotation. Higher degrees of rotation result in reduction of FO_P, LS_P, and γP. The assessment of rotation-corrected femoral offset (FO_{RC}) requires the length of FO_P, the projected gamma angle (γP), and the known gamma angle of the implant (γI): FO_{RC} = FO_P * (tan (γI) / tan (γP)). Correction of the projected leg screw length (LS_P) is explained by the factor (cos (γP) / cos (γI)).

relationship between the outer and inner angles of the triangle and lengths of the sides is fixed. The caput-collum-diaphyseal angle of the femoral nail (CCD_I) is a known variable; therefore, the gamma angle of the implant (γI) is 180° – CCD_I. After calibration, the extent of femoral offset can be directly measured in non-rotated radiographs, where the projected CCD_I (CCD_P) equals the true CCD_I (Figure 3). The calibration factor (CF) was defined as the ratio between the true diameter of the head of the femoral nail (ND, 15.5 mm) and its projected diameter (ND_P):

$$CF = ND / ND_P$$

Internal and external rotation around the femoral axis increase the projected CCD_I and decrease the projected gamma angle (γP), resulting in a reduction in the projected femoral offset (FO_P). Because the true CCD_I and the true gamma angle (γI) of the implant are known, the extent of internal and external rotation can be calculated by measuring γP or CCD_P (Kay et al. 2000). The relationship between hip rotation, the projected angles, and the lengths of the sides of the triangle is explained by the cosine function. Therefore, CCD_P can be used as a basis to infer the extent of hip rotation thus:

$$HR = \arccos(\tan(\gamma P) / \tan(\gamma I))$$

The Table gives the hip rotation in 5° steps from 0° to 90° relative to the CCD_P, and γP for implants with CCD_I ranging from 110° to 145°, also in 5° steps. The rotation-correction factor (RCF) for the adjustment of the measured FO_P is also shown in the Table. The RCF is independent from the CCD_I of the implant and is defined by:

$$RCF = (\tan(\gamma I) / \tan(\gamma P))$$

Finally, the rotation-corrected femoral offset (FO_{RC}) is calculated from the product of FO_P, the corresponding RCF and the calibration factor:

$$FO_{RC} = FO_P \cdot (\tan(\gamma I) / \tan(\gamma P)) \cdot (ND / ND_P)$$

Or simplified:

$$FO_{RC} = FO_P \cdot RCF \cdot CF$$

A coronal view in the exact plane of the femoral neck/lag screw axis was reconstructed to measure femoral offset by CT (FO_{CT}) using the same method.

We also assessed 2 alternative methods for the assessment of femoral offset on plain AP radiographs following proximal femoral nailing. The first assumes FO_P to be identical with FO (Pajarinen et al. 2004). The second (FO_{LS}) defines the combined correction and calibration factor for hip rotation as the ratio between projected and true length of the implanted lag screw (Paul et al. 2012).

Intraclass correlation coefficients for the assessment of FO_{RC} by AP hip radiographs were calculated by correlating the repeated measurements of 1 observer and of 2 independent blinded observers, respectively.

Statistics

For descriptive analysis, absolute mean values and ranges of the measured variables are reported. Variables were tested for normality using the D'Agostino-Pearson normality test

Assessment of hip rotation by analysis of the projected γ-angle. All measurements are given in degrees (°). The rotation-correction factor for the assessment of rotation-corrected femoral offset is given

CCD implant (°)	110	115	120	125	130	135	140	145	
Gamma angle (°)	70	65	60	55	50	45	40	35	Rotation correction factor
Hip rotation (°)	Projected gamma angle (°)								
90	0	0	0	0	0	0	0	0	n.a.
85	13	11	9	7	6	5	4	3	11.5
80	26	20	17	14	12	10	8	7	5.8
75	35	29	24	20	17	15	12	10	3.9
70	43	36	31	26	22	19	16	13	2.9
65	49	42	36	31	27	23	20	16	2.4
60	54	47	41	36	31	27	23	19	2.0
55	58	51	45	39	34	30	26	22	1.7
50	60	54	48	43	37	33	28	24	1.6
45	63	57	51	45	40	35	31	26	1.4
40	65	59	53	48	42	37	33	28	1.3
35	66	60	55	49	44	39	35	30	1.2
30	67	62	56	51	46	41	36	31	1.2
25	68	63	58	52	47	42	37	32	1.1
20	69	64	58	53	48	43	38	33	1.1
15	69	64	59	54	49	44	39	34	1.0
10	70	65	60	55	50	45	40	35	1.0
5	70	65	60	55	50	45	40	35	1.0
0	70	65	60	55	50	45	40	35	1.0

of hip rotation and FO_{RC} and FO_{LS}, a model-selection algorithm for multiple fractional models was applied (Sauerbrei and Royston 1999). The model that best predicted FO_{RC} and FO_{LS} was chosen. The studentized Breusch-Pagan test was performed for testing against heteroscedasticity and the Shapiro-Wilk test was used for testing the normality of the residuals. Results with p-values of < 0.05 were considered to be significant. R (version 3.0.2; R Foundation for Statistical Computing, Vienna, Austria) with package psy (version 1.1) and mfp (version 1.4.9), GraphPad Prism 4 (GraphPad Software Inc., La Jolla, CA) and Microsoft Excel 2008 for Mac version 12.3.6 were used.

Ethics

The study design was approved by the local ethics committee in May 2013 (registration number 182/12).

(omnibus K2). Exploratory analysis was performed using the two-tailed Wilcoxon matched-pair test for non-normally distributed variables (FO_{CT}, FO_{LS}, FO_P, FO_{RC}). For validation, the non-parametric Friedman and Dunn multiple-comparison tests were used. The Spearman correlation coefficient with a 95% confidence interval (CI) was calculated between FO_{RC} and FO_{CT}. Intraclass correlation with CI for the assessment of FO_{RC} was calculated for repeated measures of 1 observer and 2 independent observers. To show non-linear relationship

Results

Non-linear correlation between projected femoral offset (FO_P) and hip rotation (HR)

We found non-linear relationships between the hip rotation-dependent projected gamma angle (γP) for different implants with varying CCD_I (Table and Figure 4a), and RCF (tangent function) and the cosine-dependent correction factor (Figure 4b; see FO_{LS} and FO_{cos}).

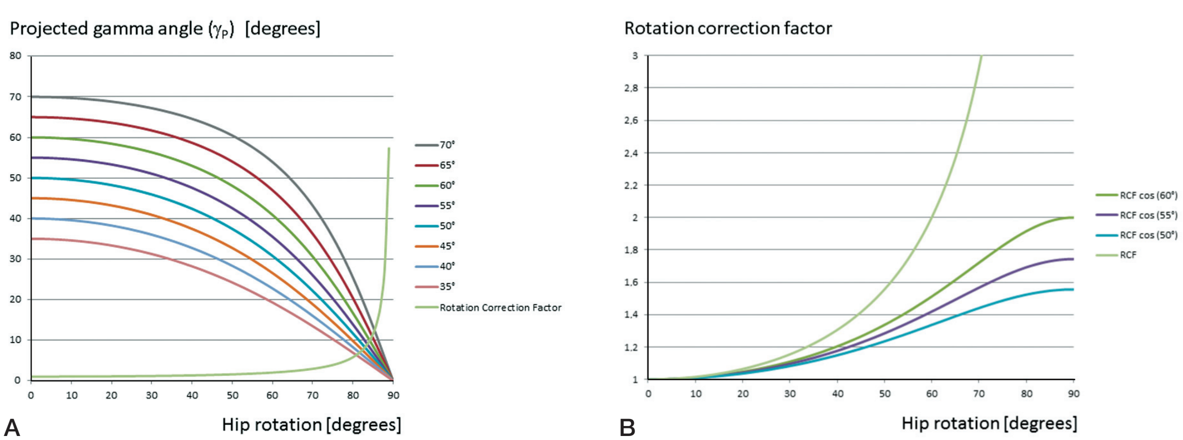

Figure 4. A. Correlation between hip rotation and projected gamma angles (γP) for implants with varying gamma angles (γI). The tangent-based rotation-correction factor (RCF) is given. B. Comparison of hip rotation correction factors for the assessment of femoral offset. The tangent-based rotation-correction factor (RCF) is independent from the gamma angle of the implant, while the cosine-based correction factor (RCF_{COS}) depends on hip rotation and implant gamma angle.

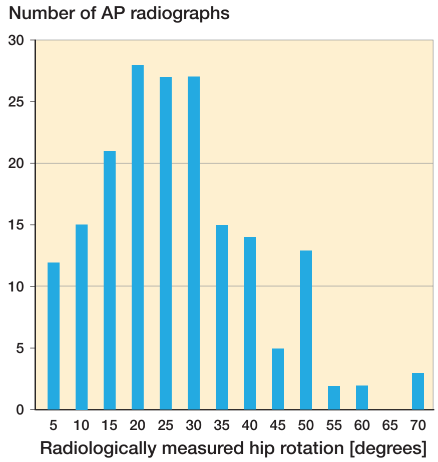

Figure 5. Distribution of radiologically assessed hip rotation in a series of 222 standardized AP radiographs of the hip following proximal femoral fractures.

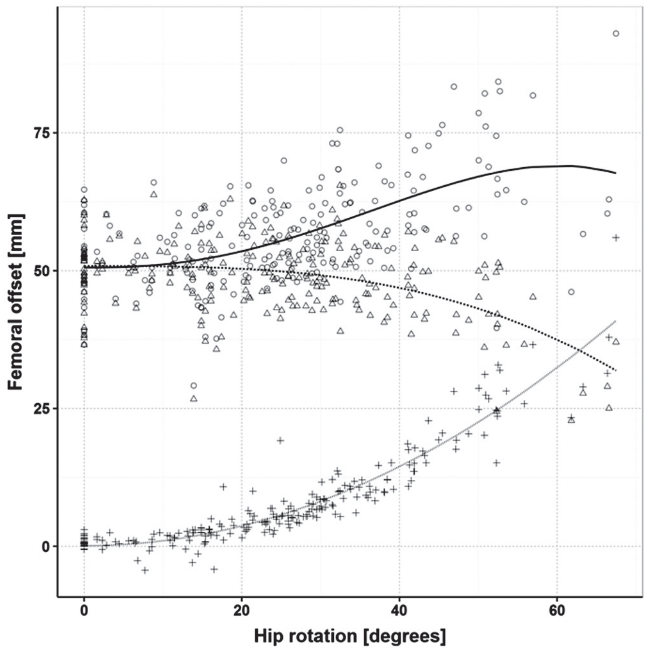

Figure 6. The y-axis represents absolute femoral offset in mm and the x-axis shows hip rotation in degrees. Rotation-corrected (circles), leg screw-corrected femoral offset (triangles), and the difference between both methods (cross) are given with polynomial trendlines.

Assessment of rotation-corrected femoral offset (FO_{RC})

FO_{RC} was assessed in 222 plain AP radiographs from 85 patients: 172 (77%) showed more than 10° of hip rotation (24° (0–68)) (Figure 5). The mean RCF was 1.2 (1–2.6) and the resulting mean FO_{RC} was 57 (29–93) mm (Figure 6).

The studentized Breusch-Pagan test showed heteroscedasticity for FO_{RC} and FO_{LS} ($p < 0.001$ for both). The p-values for normality of the residuals for FO_{RC} and FO_{LS} were 0.06 and 0.1.

The mean FO_P measured directly without correction factors was 49 (22–65) mm discrepant from FO_{RC} ($p < 0.001$). Using lag screw length to calibrate and correct FO_P resulted in a mean correction factor of 0.63 (0.12–1.23) and thus a mean lag screw-corrected femoral offset (FO_{LS}) of 49 (23–66) mm. The difference between FO_{RC} and FO_{LS} was statistically significant ($p < 0.001$).

Validation by CT

Anteroposterior radiographs of the hip were compared with corresponding CT scans in 25 patients. Mean FO_{CT} was 57 (34–71) mm, mean FO_{RC} 58 (36–74) mm, and mean FO_{LS} 52 (24–72) mm. The Friedman test showed significant differences between the means ($p < 0.001$) and post hoc analysis found significant differences between FO_{CT} and FO_{LS}, as well as FO_{LS} and FO_{RC}. Mean FO_{RC} and FO_{CT} were not significantly different. The correlation coefficient for FO_{CT} and FO_{RC} was 0.94 (95% CI: 0.88–0.97).

Intraclass correlation coefficient for intra- and inter-rater reliability

Intraclass coefficients for FO_{RC} for inter-rater and intra-rater reliability were 1.0 and 1.0.

Discussion

The biomechanical importance of obtaining adequate femoral offset after hip replacement is clear: it influences the stability of the articulation of the prosthesis (Matsushita et al. 2009), leg length (Maloney and Keeney 2004), component wear (Sakalkale et al. 2001), the lever arm of the abductor muscles (McGrory et al. 1995) and impingement-free range of motion (McGrory et al. 1995, Matsushita et al. 2009). Furthermore, there has been recent debate about the necessity of preserving femoral offset during fixation of proximal femoral fractures (Eijer et al. 2001, Paul et al. 2012). The best radiological means of measuring femoral offset is CT; however, the substantive radiation dose, cost, and artifacts caused by metallic implants mean that it is not routinely used in clinical practice for postoperative examinations or in large cohort studies. Plain AP radiographs of the hip or pelvis remain the accepted method for the radiological assessment of femoral offset. Merle et al. (2012) have shown that clinically relevant projection errors can occur depending on the position of the central beam, and they recommended a standardized radiographic technique paying attention to patient positioning and a defined internal rotation of the leg. These standards cannot always be achieved due to contractures, pain, and limited patient compliance. Even defined internal rotation of the leg does not reliably neutralize hip rotation due to the existence of femoral ante- and retroversion and unpredictable compensatory effects from the ipsilateral ankle and knee joint (Lecerf et al. 2009).

Dunn (1952) and Rippstein (1955) first recognized the influence of hip rotation on the radiological appearance of the proximal femur, while more recently the effect of hip rotation on the projected femoral neck-shaft angle and femoral offset has been described in detail (Lindgren and Rysavy 1992, Kay et al. 2000, Meyer and Kotecha 2008). Nevertheless, there is still no generally accepted approach to measuring femoral offset on plain AP hip radiographs that satisfactorily accounts for hip rotation. Some authors have assumed that the FO_P equals the true femoral offset, and have therefore made no correction for hip rotation (Pajarinen et al. 2004). Other approaches to correct for hip rotation have been proposed (Lindgren and Rysavy 1992, Meyer and Kotecha 2008), including the analysis of the depiction of anatomic landmarks or implant features. For example, Paul et al. (2012) assumed a direct correlation between projected leg screw length and projected femoral offset (FO_{LS}):

$FO_{LS} = FO_P \bullet LS / LS_P$

This approach partially accounts for hip rotation, and the correction of femoral offset can be explained by the cosine function (FO_{cos}):

$FO_{cos} = FO_P \bullet (\cos(\gamma P) / \cos(\gamma I)) \bullet (ND / ND_P)$

However, the accuracy of the measurement of the length of the projected lag screw decreases with increasing hip rotation. Here, the non-orthogonal depiction of the tip and the base of the screw are limiting factors. Consequently, we developed a mathematical method to provide a rotation-dependent correction factor to allow the accurate assessment of femoral offset on plain AP hip radiographs after proximal femoral nailing. Hip rotation was assessed by the rotation-dependent projection of the CCD_I (Table). We validated the mathematical relationship and its clinical application in vivo using implanted proximal femoral nails as 3-D intracorporeal radio-opaque markers. The mathematical model was clearly superior to the method based on the cosine function of the previously described approach (FO_{LS}).

We found high variability of measured hip rotation. As there was a non-linear correlation between hip rotation and FO_P, minor rotational malposition would be expected to have little effect on the FO_P. However, the surprisingly high proportion of radiographs with hip rotation exceeding 20° emphasizes the importance of using FO_{RC}. Our mathematical model allowed precise prediction of the femoral offset and was validated by CT; however, the RCF was overestimated if the hip was very rotated, which can be explained by simultaneous non-rotational malposition in particular positions when the hip is flexed.

Standardization of the acquisition of radiographic images is essential for accurate measurement of distances and their biomechanical interpretation (Levine et al. 2010). While the most common calibration method is based on an extracorporeal metallic sphere with a defined diameter positioned at the supposed vertical height of the center of the hip, intracorporeal implants have also been used successfully (Meyer and Kotecha 2008, Paul et al. 2012). Following anterograde intramedullary femoral nailing, the proximal diameter of the nail can be reliably measured without the risk of rotational errors. Furthermore, its location in the region of interest and in the correct vertical plane offers advantages over extracorporeal calibration standards.

Our study had some limitations. Our mathematical model showed excellent agreement with the data generated experimentally by Meyer and Kotecha (2008), and although it does not provide experimental proof of the method, it explains the mathematical basis of the lag screw-dependent approach published by Paul et al. (2012) (FO_{cos}). We studied only one type of intramedullary nail; however, the method is likely to be applicable to a variety of osteosynthetic and prosthetic implants with a defined radio-opaque area for calibration and known CCD_I. The exact measurement of the projected CCD is essential for the assessment of femoral rotation; there is a systematic increase in the femoral offset if the femoral shaft axis is substituted with the femoral nail axis.

In AP radiographs with extensive internal or external rotation of the hip, the applicability and the precision of the method are impaired, as implied by the assumption of heteroscedasticity shown in Figure 6. First, the position of the center of the femoral head on AP radiographs would probably not coincide with its position on semi-axial or axial films. Second, the axis of the femoral shaft is significantly influenced by the femoral antecurvature, resulting in misinterpretation of the femoral offset. Furthermore, our method cannot be used to measure femoral offset on AP radiographs with considerable flexion or extension of the hip. Both alter the projected CCD_I, resulting in misinterpretation of hip rotation and femoral offset. Hip flexion and extension are easily detectable on AP radiographs by non-orthogonal depiction of the head of the femoral nail, leading to an elliptic appearance of the proximal end. Therefore, we do not recommend that our method be used to correct radiographs with > 45° hip rotation; acquisition of adequately adjusted radiographs or CT scans should be considered in these cases (Lecerf et al. 2009).

In conclusion, we have presented a mathematical explanation for the rotation-dependent projection of femoral offset, and show that it can be reliably assessed on AP radiographs following proximal femoral nailing, as long as hip rotation is adequately accounted for. Application of these findings to large cohorts of patients could enhance the accuracy of the radiological assessment of the femoral offset and might improve our understanding of hip biomechanics.

PL and CKB developed the study design and performed data collection, analysis, interpretation, and writing. MF, AG, BB, SR, AM, and TR performed data interpretation and critical revision.

We are grateful for useful advice and suggestions from Hagen Langhuth, MSc, Jochen Schröder, MD, Vinzenz Pfeifer, and Laura Waltl, MSc.

No competing interests declared.

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