

Prediction of three-dimensional femoral offset from AP pelvis radiographs in primary hip osteoarthritis

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Abstract

Background

In pre-operative planning for total hip arthroplasty (THA), femoral offset (FO) is frequently underestimated on AP pelvis radiographs as a result of inaccurate patient positioning, imprecise magnification, and radiographic beam divergence. The aim of the present study was to evaluate the accuracy and reliability of predicting three-dimensional (3-D) FO from standardised AP-pelvis radiographs.

Methods

In a retrospective cohort study, pre-operative AP-pelvis radiographs, AP-hip radiographs and CT scans of a consecutive series of 345 patients (345 hips, 146 males, 199 females, mean age 60 (range:40-79) years, mean body-mass-index 27 (range:29-57) kg/m²) with primary end-stage hip OA were reviewed. Patients were positioned according to a standardised protocol and all images were calibrated. Using validated custom programmes, FO was measured on corresponding radiographs and CT scans. Measurement reliability was evaluated using intra-class-correlation-coefficients. To predict 3-D FO from AP-pelvis measurements and to assess the accuracy compared to CT, the entire cohort was randomly split into subgroups A and B. Gender specific regression equations were derived from group A (245 patients) and the accuracy of prediction was evaluated in group B (100 patients) using Bland-Altman plots.

Results

In the entire cohort, mean FO was 39.2 mm (95%CI: 38.5-40.0 mm) on AP-pelvis radiographs, 44.1 mm (95%CI: 43.4-44.9 mm) on AP-hip radiographs and 44.6 mm (95%CI: 44.0-45.2 mm) on CT scans. In group B, we observed no significant difference between gender specific predicted FO (males: 48.0 mm, 95%CI: 47.1-48.8 mm; females: 42.0 mm, 95%CI: 41.1-42.8 mm) and FO as measured on CT (males: 47.7 mm, 95%CI: 46.1-49.4 mm, p=0.689; females: 41.6 mm, 95%CI: 40.3-43.0 mm, p=0.607).

Conclusions

The present study suggests that **FO** can be accurately and reliably predicted from AP-pelvis radiographs in patients with primary end-stage hip osteoarthritis. Our findings support the surgeon in pre-operative templating on AP-pelvis radiographs and may improve offset and

limb length restoration in THA without the routine performance of additional radiographs or CT.

Key Words: Hip, Osteoarthritis, Arthroplasty, Planning, Radiography, CT

Introduction

Accurate restoration of physiological biomechanics is a major technical goal in contemporary total hip arthroplasty (THA). Besides providing the patient with a better functional outcome in terms of good range of motion¹ and abductor muscle strength², it is essential to prevent long-term adverse effects such as dislocation³, impingement⁴ and accelerated wear⁵.

In pre-operative planning, accurate and reliable assessment of femoral offset (FO) is crucial as it suggests the appropriate size and design of prosthetic components. Anteroposterior (AP) pelvis radiographs are commonly used in pre-operative templating for THA because they provide additional information regarding pelvic and contralateral hip anatomy, and allow evaluation of leg length discrepancies⁶. However, it is well recognised that FO is significantly underestimated on AP pelvis views compared to three-dimensional (3-D) FO as measured on computed tomography (CT)⁷. Three major factors have been identified for this observation: (1) failure to reliably position the patient with the femoral neck in the coronal plane as a result of high variability in femoral anteversion⁸ or external rotation contracture⁹, (2) imprecise calibration and (3) the effect of radiographic beam divergence. As a consequence, several studies have promoted CT-based surgical planning^{10, 11}. Considering additional radiation exposure, higher costs, limited availability and a lack of evidence for improved clinical outcome in the long-term, this seems questionable.

It has been previously reported that femoral offset is significantly underestimated on AP pelvis radiographs but can be more accurately and reliably assessed on standardised AP hip radiographs compared to CT in patients with primary end-stage hip OA¹². Moreover, a linear relationship between corresponding FO measurements performed on AP pelvis radiographs, AP hip radiographs and CT scans has been previously suggested¹².

In the present study, we aimed to determine (1) whether three-dimensional femoral offset as measured on CT scans can be predicted from FO measurements performed on AP pelvis views, and (2) whether predicted FO values compare favourably to measurements performed on AP hip views.

Materials and Methods

Cohort

In a retrospective cohort study, we reviewed a consecutive series of 597 patients who had undergone primary THA for end-stage hip osteoarthritis (OA) with a custom-made cementless femoral component between June 2008 and December 2009. Each patient received a pre-operative standardised AP pelvis radiograph, AP hip radiograph and a CT scan of the affected hip, and all images were digitally stored in a generic DICOM format.

In order to obtain normative values of FO measurements on the three corresponding modes of imaging, we only included patients with primary hip osteoarthritis. Patients with a history of trauma, infection, rheumatic disease, developmental dysplasia of the hip (DDH), previous pelvic and/or femoral osteotomy, avascular necrosis (AVN) of the femoral head, Legg–Calvé–Perthes disease, or slipped capital femoral epiphysis (SCFE) were excluded from the present study. To quantitatively identify patients with acetabular undercoverage, further exclusion criteria were defined as a center-edge angle (CE) < 20 degrees¹³, an acetabular angle (AA) > 42 degrees¹⁴ and an acetabular index (AI) < 38 ¹⁵.

According to the criteria stated above, 252 patients were excluded from the initial cohort, leaving 345 patients (146 males, 199 females, mean age 60 (range: 40-79) years, mean body-mass- index (BMI) 27 (range: 29-56) kg/m², Table 1) that were included in the present study. The study was approved by the institutional review board (reference S-272/2009) and carried out in accordance with the Declaration of Helsinki of 1975, as revised in 2008.

To evaluate the validity and accuracy of predicting 3-D FO as measured on CT from FO measurements performed on AP pelvis views, the study cohort of 345 patients was randomly split into two groups. Group A comprised 245 patients (101 males, 144 females, mean age 60

(range: 40 to 79) years, mean BMI 27 (range: 19 to 56) kg/m²); and group B comprised 100 patients (45 males, 55 females, mean age 60 (range: 44 to 72) years, mean BMI 27 (range: 19 to 41) kg/m²). In group A, corresponding FO measurements on AP pelvis radiographs (FO_p) and CT scans (FO_c), were used to derive regression equations for the entire group, and for males and females separately, to predict 3-D FO from AP pelvis views (FO_{pred}). Derived Regression equations from measurements in group A were applied to FO_p measurements in group B.

The validity and accuracy of mean FO_{pred} for was assessed in group B with reference to FO_c for all patients, and for both genders separately. In order to compare FO_{pred} to FO measurements performed on AP hip views (FO_h), the frequencies of clinically significant over- or underestimation² (>12%) with reference to FO_c were evaluated.

Imaging Protocol

For all patients, low-centered AP pelvis radiographs and AP hip radiographs were taken in a supine position according to a standardised radiographic protocol to achieve reproducible projection. To correct for effects of magnification, a metal calibration sphere of 25 mm was positioned on the inner thigh at the anterior-posterior level of the femoral head.

For AP pelvis radiographs, the crosshair of the beam was centred on the pubic symphysis and both legs were internally rotated by 15 degrees using a foot retainer. For AP hip radiographs, the x-ray tube was moved to direct the central beam to the centre of the femoral head of the diseased hip. For AP hip radiographs, the crosshair of the beam was directed to the midpoint between the anterior superior iliac spine and the symphysis to direct the beam on the centre of the femoral head of the affected hip. The affected leg was internally rotated and retained so that the greatest prominence of the greater trochanter was palpated at its most lateral position to bring the femoral neck into the coronal plane. When internal rotation of the leg was not

sufficient due to external rotation contracture, the affected hip was additionally elevated on the AP hip view using a wedge.

During the study period, two x-ray tubes were in use: Canon CXDI series [Canon Inc., Tokyo, Japan] and Philips Bucky Diagnost VE VT [Royal Philips Electronics Inc., Amsterdam, Netherlands]. The tube-to-film distance was 1150 mm, with the tube orientation perpendicular to the table.

For the CT scans, patients were positioned supine, with legs in neutral rotation as shown by scout views. The scans were obtained in three sets: from the cranial aspect of the acetabulum to below the lesser trochanter, from below the lesser trochanter to 50 mm distally of the femoral isthmus and 4 slices of the femoral condyles. Slice spacing of 4 mm, 8 mm and 2 mm was used, respectively. All hip CT scans were performed using a Toshiba Aquilion 16 CT scanner [Toshiba Corp., Tokyo, Japan] with gantry tilt 0, 120 kV and a field of view (FOV) of 250 mm.

Radiographic measurements

A commercially available templating programme, *TraumaCad* [version 2.2, Voyant Health, Petach-Tikva, Israel]¹⁶, was used to measure CE¹³, AA¹⁴ and AI¹⁵ on AP pelvis radiographs.

A previously validated custom MATLAB program [version 7.10, The MathWorks Inc., MA, USA] was used to determine the centre of the femoral head (HC), the head diameter (HD) and the femoral shaft axis, and the femoral neck axis on AP pelvis and AP hip radiographs (Figure 1). A circle tool was used to define the head diameter and the co-ordinates of its centre. On the femoral diaphysis, two points on the medial and lateral cortex 20 mm below the lesser trochanter, and two points at the level of the femoral isthmus were defined. The midpoints of these point pairs determined the femoral shaft axis. On the femoral neck, two corresponding point pairs were placed at the superior and inferior cortex of the upper and

lower neck, and the line connecting their midpoints determined the femoral neck axis. All points were manually selected and automatically saved. FO was calculated as the perpendicular distance from the centre of the femoral head to the femoral shaft axis. The neck-shaft-angle (NSA) was calculated as the angle between the femoral shaft axis and the femoral neck axis. Measurements on AP pelvis radiographs were labeled FO_p , NSA_p and HD_p , and on AP hip radiographs FO_h , NSA_h and HD_h , respectively.

CT measurements

In addition to the 2-D measurements, a second validated custom MATLAB programme was used to measure FO and femoral anteversion (FA) on the CT image set. The programme enabled the user to select points from pre-selected axial CT slices and performed calculations in the 3-D co-ordinate system of the CT scanner (Figure 2).

For the 3-D calculation of FO (FO_c) and head diameter (HD_c), three axial slices were selected (s1, s3, s4, Figure 3). HD_c and the centre of the femoral head were determined on the slice with the femoral head at its largest diameter (s1) using a circle tool. The femoral shaft axis was defined by the centroid^{17, 18} (s3) and the centre of the isthmus (s4); FO_c was then calculated as the perpendicular distance from the femoral shaft axis to the centre of the femoral head.

For the calculation of femoral anteversion (FA), two axial slices were selected (s2, s5, Figure 2). On s2, the femoral neck axis was defined using the single slice method according to Sugano¹⁹, and on s5 the posterior condylar axis was defined by the most posterior aspects of the lateral and medial condyles. FA was taken to be the angle between the femoral neck axis and the posterior condylar axis.

Measurement reliability

Intra- and inter-observer reliabilities for 20 randomly selected corresponding AP pelvis radiographs, AP hip radiographs and CT scans were evaluated by two independent and blinded observers using single-measure intra-class-correlation coefficients (ICC) with a two-way-random effects model for absolute agreement.

Statistical analysis

The distributions of variables were examined in descriptive histograms and box plots, and a normal distribution was assumed for all analyses. For descriptive analysis, absolute mean values for FO were expressed in mm with 95% confidence intervals (95%CI). A Kolmogorov-Smirnov test was used to identify normal distribution of the variables. Differences in mean FO were expressed in absolute (mm, 95%CI) and relative (%) values. Distributions of FO values were compared using paired-samples t-tests for paired observations and independent-samples t-tests for unpaired observations. Results with p values <0.05 were considered as significant, p values of <0.001 were considered as highly significant. Scatter plots and Pearson's correlation coefficient (r) were used to evaluate associations between continuous variables. Correlation was characterised as poor (0.00-0.20), fair (0.21-0.40), moderate (0.41-0.60) good (0.61-0.80), or excellent (0.81-1.00)²⁰. Simple linear regression was performed to predict FO_c from FO_p. Stepwise multiple linear regression with FO_c as the dependent variable and FO_p, NSA_p HD_p, BMI, height, weight and age as the independent variables was used to determine additional significant predictor variables from the dataset. Statistical analysis was performed using PASW Statistics 18 [SPSS Inc. an IBM company, IL, USA].

Source of Funding

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Results

Measurement reliability

Intra-observer ICC was good for NSA_h (0.797) and excellent for FO_p (0.993), FO_h (0.990), FO_c (0.990), NSA_p (0.926), HD_p (0.886), HD_h (0.906), HD_c (0.933) and FA (0.984). Inter-observer ICC also showed good correlation for NSA_h (0.751) and excellent correlation for FO_p (0.986), FO_h (0.977), FO_c (0.991), NSA_p (0.887), HD_p (0.812), HD_h (0.848), HD_c (0.866) and FA (0.950).

Radiographic and CT findings

In the entire cohort, mean FO_p (39.2 mm, 95%CI: 38.5 to 40.0 mm) was significantly lower than mean FO_h (44.1 mm, 95%CI: 43.4 to 44.9 mm, $p<0.001$) with mean difference of 4.9 mm (95%CI: 4.6 to 5.3 mm, 13%, Table 2).

With reference to mean FO_c (44.6 mm, 95%CI: 44.0 to 45.2 mm), FO_p was under-estimated by 5.4 mm (95%CI: 4.8 to 6.0 mm, 13%) and FO_h was under-estimated by 0.4 mm (95%CI: -0.1 to 0.9 mm, 1%). There was a highly significant difference between mean FO_c and FO_p ($p<0.001$); in contrast, no significant difference between FO_c and FO_h ($p=0.092$) was observed (Table 2).

Regression Analysis

In group A, we observed a significant correlation between FO_p and FO_c ($r=0.642$, $p<0.001$, Figure 3). From the regression analysis, Equation (1) was derived to predict FO as measured on CT from measurements on AP pelvis views:

$$FO_c = 0.50 \times FO_p + 24.8 \quad (R^2=0.412) \quad \text{Equation (1)}$$

Bland-Altman plots demonstrated that the agreement between FO_p and FO_c was biased (mean bias: 5.6 mm, 95%CI: 4.5 to 6.8 mm). FO_h and FO_c showed good agreement (mean bias: 0.45 mm, 95%CI: -0.6 to 1.5 mm). Best agreement was seen between FO_{pred} and FO_c (bias: 0.2 mm, 95%CI: -0.1 to 1.1 mm, Figure 4).

When considering males and females separately, corresponding FO_p and FO_c measurements demonstrated significant correlations for males ($r=0.537$, $p<0.001$) and for females ($r=0.660$, $p<0.001$). Regression analysis was applied to each gender to derive Equation (2) for males and Equation (3) for females, respectively:

$$FO_c = 0.39 \times FO_p + 31.9 \quad (R^2=0.288) \quad \text{Equation (2)}$$

$$FO_c = 0.45 \times FO_p + 25.4 \quad (R^2=0.436) \quad \text{Equation (3)}$$

Prediction of FO in group B using Equation (1) resulted in a highly significant under-estimation by 2.3 mm (95%CI: 1.2 to 3.5 mm, 5.2%, $p<0.001$) in males and in a significant over-estimation by 1.5 mm (95%CI: -2.8 to -0.3 mm, 3.6%, $p=0.013$) in females. Using gender specific prediction equations (equation 2: males) and (equation 3: females), no significant difference between FO_{pred} and FO_c was observed for neither the males (-0.2 mm, 95%CI: -1.4 to 0.9 mm, 0.5%, $p = 0.689$, Figure 5 A) nor the females (-0.3 mm 95%CI: -1.5 to 0.9 mm 0.7%, Figure 5 B).

Compared to FO_c , FO_p demonstrated a clinically relevant under-estimation ($>12\%$) in 53% of all cases in group B. FO_h resulted in a relevant under-estimation in 13% but also in an over-estimation in 10%. For males, equation (2) could predict FO_c more accurately with under-estimation rates of 7% and over-estimation rates of 2% (males: 12% of $FO_c = 5.8$ mm).

However, in females under-estimation of gender-specific FO_{pred} (equation (3)) occurred in 13%, and over-estimation 11% (females: 12% of $FO_c = 5.1$ mm).

A stepwise regression model performed for group A identified patient height (m) as the only other significant independent variable; all other tested variables were not significant.

The following gender specific regression equations (males: equation (4), females: equation (5)) including height (m) were derived. The coefficient of determination (R^2) improved slightly, however, this did not improve the accuracy of the prediction in group B.

$$FO_c = 0.38 \times FO_p + 14.41 \times \text{height (m)} + 6.81 \quad (R^2=0.299) \quad \text{Equation (4)}$$

$$FO_c = 0.34 \times FO_p + 14.43 \times \text{height (m)} + 2.03 \quad (R^2=0.458) \quad \text{Equation (5)}$$

Discussion

The original goal of total hip arthroplasty (THA) was to provide good pain relief and durable component fixation in the long-term. Over the last three decades, the ongoing success of THA has led to a continuous rise in implantation numbers with indications being extended to younger, more active and demanding patients²¹. In patients undergoing THA for end-stage OA, a high variability in morphologic and geometric parameters of the hip joint is observed and individual restoration of a physiological hip geometry with high accuracy has become a major technical goal of THA. Several clinical advantages are associated with accurate femoral offset- and leg length reconstruction as they improve the functional outcome^{1, 2, 22} and minimise the risk of THA specific complications^{23, 24}.

Accurate and reliable pre-operative planning is crucial, and is widely performed on AP pelvis radiographs. Standardised recommendations of patient positioning during radiography with 15 degrees of internal rotation of the lower limbs have, therefore, been made to ensure reproducible anatomical projection of the femoral neck. However, several studies have demonstrated that radiographic assessment of FO has limited reliability^{11, 25}, which may adversely affect intra-operative soft-tissue balancing. CT is considered as the gold standard as it allows true 3-D evaluation of hip geometry, and consequently allows a more accurate selection of the implant and its position²⁵.

The present study evaluated the accuracy and reliability of predicting 3-D femoral offset from standardised AP pelvis radiographs based on the underlying observation of a linear relationship between corresponding FO measurements performed on AP pelvis radiographs and CT scans¹².

To predict 3-D FO from AP pelvis measurements and assess the accuracy compared to CT, the entire cohort was randomly split into subgroups A and B. Gender specific regression equations were derived from group A (245 patients) and then applied to FO_p measurements performed in group B (100 patients).

Measurements of FO on both radiography and CT scans showed excellent intra- and inter-observer reliability, and a linear correlation of corresponding FO measurements on all three modes of imaging was seen. Calculating FO_{pred} with use of gender specific regression equations, no significant difference between mean FO_{pred} and FO_c was seen in group B. Therefore, the present study suggests that 3-D femoral offset may be accurately predicted from FO measurements performed on AP pelvis views with use of the provided equations. Moreover, the results demonstrate that the given equations reduce the occurrence of clinically relevant over- or underestimation (> 12%) of FO_h.

The present study has a number of limitations:

Firstly, the target population of the present study were patients with primary end-stage hip OA. Care should therefore be taken when applying the provided equations to patients with secondary forms of OA or advanced deformity. For patients with primary OA, the present cohort can be considered as representative with regard to patient demographics. This limitation should be put into perspective as the leading diagnosis for THA is primary OA²⁶.

The present definition of primary OA did not exclude the presence of coxa profunda and of hip OA related to cam- or pincer-type impingement syndromes. Both bony overcoverage of the head as well as morphological alterations of the head-neck junction as possible risk factors for OA²⁷ were not assessed as these changes might be subtle and cannot be reliably identified in the present cohort with end-stage OA due to the retrospective nature of this study. In the present cohort, 16 patients had retroverted femora

with mean FA of -2.7 degrees (range: -6.7 to 3.5 degrees, 95%CI: -3.9 to -1.4 degrees). Mean difference between FO_{predicted} and FO_{ct} was 0.4 mm for males (n=3, 95%CI: -7.0- 7.7 mm) and -0.2 mm for females (n=13, 95%CI: -1.9- 1.7 mm), suggesting that mild retroversion did not increase in the error of prediction.

Second, for FO measurements on CT, we did not use the long axis of the femur (centroid of proximal femoral metaphysis to centre of knee) as reported previously²⁸. In the present study, FO_{ct} measurements were performed based on the longitudinal axis of the proximal femur (centroid of proximal femoral metaphysis to centre of femoral isthmus) in order to represent femoral offset measurements as performed on plain radiography. In the entire study cohort, the observed absolute mean values for FO_{ct} (44.6 mm) and FA (14.0 degrees) on CT scans compare well with reported values in the literature^{11, 29, 30}. Third, we cannot retrospectively identify patients whose affected hip was elevated for the AP hip radiographs by 15 degrees to compensate for external rotation contracture. Elevation seems beneficial to bring the femoral neck into the coronal plane minimising the effect of rotation; however, this may have affected the object-to-film distance and might therefore be the cause of the observed overestimation of FO (> 5mm) on AP hip radiographs in 13% of patients in group B .

To our knowledge, this is the first study that demonstrates the validity and accuracy of predicting true 3-D femoral offset from plain radiography in patients with primary hip OA. We do not question CT as the gold standard in the assessment of proximal femoral geometry. The provided approach does not entirely account for imprecision in measurement on plain radiographs. Yet, our findings support the surgeon in pre-operative planning on AP pelvis radiographs and may improve femoral offset and limb length restoration in THA without the routine need for additional AP hip radiographs or CT. The suggested prediction model

reduces radiation exposure and per-patient costs and can be easily incorporated in digital planning tools which are widely used.

In conclusion, the present study confirms that a linear relationship between femoral offset measurements on corresponding AP pelvis radiographs and CT scans exists. The provided regression equations account for the adverse effects of positioning inconsistencies, imprecise calibration and beam divergence in conventional radiography and limit the occurrence of clinically relevant over- or underestimation of FO on AP hip radiographs. Although, CT clearly remains the most accurate option to assess pelvic and femoral anatomy, true 3-D femoral offset can be accurately and reliably predicted from AP pelvis radiographs in patients with primary OA.

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Role of the Funding Source and Conflict of Interest

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Table 1

	Entire cohort (n=345)	Males (n=146)	Females (n=199)
Gender in cohort (%)	100.0	42.3	57.7
Age (years)	60.4 (range: 40-79) (95%CI: 59.6-61.1)	60.5 (range: 43-72) (95%CI: 59.3-61.6)	60.3 (range: 40-79) (95%CI: 59.3-61.3)
Weight (kg)	78.5 (range: 46-173) (95%CI: 76.8-80.1)	85.3 (range: 54-138) (95%CI: 83.1-87.5)	73.3 (range: 46-173) (95%CI: 71.2-75.4)
Height (meters)	1.70 (range: 1.46-1.97) (95%CI: 1.69-1.71)	1.77 (range: 1.60-1.97) (95%CI: 1.76-1.78)	1.65 (range: 1.46-1.88) (95%CI: 1.64-1.66)
BMI (kg/m ²)	27.0 (range: 19.2-56.5) (95%CI: 26.5- 27.5)	27.1 (range: 19.8-42.6) (95%CI: 26.5-27.8)	26.9 (range: 19.2-56.5) (95%CI: 26.2-27.7)

Table 1
Demographic data of the entire cohort, male patients and female patients.

Table 2

	Entire cohort (n=345)	Males (n=146)	Females (n=199)
FO _p (mm)	39.2 (range: 15.9-59.1) (95%CI: 38.5-40.0)	41.5 (range: 18.4-59.1) (95%CI: 40.4-42.7)	37.5 (range: 15.9-51.9) (95%CI: 36.6-38.4)
FO _h (mm)	44.1 (range: 21.4-61.5) (95%CI: 43.4-44.9)	47.6 (range: 26.2-61.5) (95%CI: 46.6-48.7)	41.6 (range: 21.4-57.9) (95%CI: 40.7-42.5)
FO _c (mm)	44.6 (range: 26.9-66.2) (95%CI: 44.0-45.2)	48.0 (range: 33.9-66.2) (95%CI: 47.1-48.8)	42.1 (range: 26.9-61.0) (95%CI: 41.4-42.7)
HD _p (mm)	46.8 (range: 36.5-57.7) (95%CI: 46.3-47.2)	49.7 (range: 41.1-57.7) (95%CI: 49.2-50.3)	44.6 (range: 36.5-57.6) (95%CI: 44.1-45.0)
HD _h (mm)	47.7 (range: 35.0-59.8) (95%CI: 47.3-48.2)	51.2 (range: 41.4-59.8) (95%CI: 50.6-51.8)	45.2 (range: 35.0-53.8) (95%CI: 44.8-45.7)
HD _c (mm)	45.8 (range: 34.7-61.6) (95%CI: 45.3-46.3)	49.3 (range: 36.8-61.0) (95%CI: 48.6-49.9)	43.2 (range: 34.7-61.6) (95%CI: 42.7-43.7)
FA (degrees)	14.0 (range: -6.7-56.8) (95%CI: 13.0-15.0)	13.3 (range: -3.0-35.9) (95%CI: 11.9-14.6)	14.5 (range: -6.7-56.8) (95%CI: 13.1-16.0)
NSA _p (degrees)	130.8 (range: 113.0-157.6) (95%CI: 130.0-131.6)	131.5 (range: 113.0-157.6) (95%CI: 130.3-132.6)	130.3 (range: 113.6-153.7) (95%CI: 129.2-131.4)
NSA _h (degrees)	125.3 (range: 111.4-148.9) (95%CI: 124.7-125.9)	125.2 (range: 113.5-143.6) (95%CI: 124.3-126.1)	125.4 (range: 111.4-148.9) (95%CI: 124.5-126.3)
FO _h - FO _p (mm)	4.9 (range: -2.1-20.9) (95%CI: 4.6-5.3)	6.1 (range: -0.8-20.9) (95%CI: 5.5-6.7)	4.1 (range: -2.1-15.2) (95%CI: 3.7-4.5)
FO _h - FO _p (%)	12.6	14.7	10.9
p values (FO _h - FO _p)	< 0.001	< 0.001	
FO _c - FO _p (mm)	5.4 (range: -8.8-24.6) (95%CI: 4.8-6.0)	6.4 (range: -6.4-24.6) (95%CI: 5.5-7.4)	4.6 (range: -8.8-24.2) (95%CI: 3.8-5.3)
FO _c - FO _p (%)	13.7	15.5	12.2
p values (FO _c - FO _p)	< 0.001	0.002	
FO _c - FO _h (mm)	0.4 (range: -14.3-21.3) (95%CI: -0.1-0.9)	0.3 (range: -10.1-14.7) (95%CI: -0.4-1.1)	0.5 (range: -14.3-21.3) (95%CI: -0.2-1.2)
FO _c - FO _h (%)	1.0	0.7	1.2
p values (FO _c - FO _h)	0.092	0.733	

Table 2

Mean values (range) for femoral offset (FO), head diameter (HD), femoral anteversion (FA) and neck-shaft-angle (NSA) with 95% CI for the entire cohort, male patients and female patient, and mean differences in FO between AP pelvis (FO_p) and AP hip (FO_h) radiographs and between AP radiographs and CT (FO_c) given in absolute (mean (range), 95%CI) and relative (%) values.

Table 3

	Group A (n=245)	Males (n=101)	Females (n=144)
FO _p	39.4 (range: 16.3-55.0) (95%CI: 38.5-40.3)	41.7 (range: 18.4-55.0) (95%CI: 40.4-43.0)	37.8 (range: 16.3-51.9) (95%CI: 36.7-38.9)
FO _h	44.2 (range: 21.4-61.2) (95%CI: 43.4-45.1)	47.8 (range: 26.2-61.2) (95%CI: 46.6-49.1)	41.7 (range: 21.4-57.9) (95%CI: 40.7-42.7)
FO _c	44.7 (range: 30.9-66.2) (95%CI: 44.0-45.4)	48.1 (range: 39.7-66.2) (95%CI: 47.1-49.1)	42.3 (range: 30.9-61.0) (95%CI: 41.5-43.0)

Table 3

Femoral offset measured on AP pelvis radiographs (FO_p), AP hip radiographs (FO_h) and CT scans (FO_c) given as absolute (mean (range), 95%CI) values for the entire group A, males and females.

Table 4

	Group B (n=100)	Males (n=45)	Females (n=55)
FO _p	38.8 (range: 15.9-59.1) (95% CI: 37.3-40.2)	41.2 (range: 24.2-59.1) (95% CI: 38.9-43.4)	36.8 (range: 15.9-47.2) (95% CI: 34.9-38.6)
FO _h	43.9 (range: 24.1-61.5) (95% CI: 42.5-45.3)	47.2 (range: 33.1-61.5) (45.2-49.2)	41.3 (range: 24.1-51.0) (95% CI: 39.5-43.0)
FO _c	44.4 (range: 26.9-60.3) (95% CI: 43.2-45.6)	47.7 (range: 33.9-60.3) (95% CI: 46.1-49.4)	41.6 (range: 26.9-53.5) (95% CI: 40.3-43.0)
FO _{pred} using Equation (1) [0.50*FO _p +24.8] (mm)	44.2 (range: 32.8-54.3) (95% CI: 43.4-44.9)	45.4 (range: 36.9-54.3) (95% CI: 44.2-46.5)	43.2 (range: 32.8-48.4) (95% CI: 42.3-44.1)
FO _c – FO _{pred} (mm)	0.2 (range: -13.1-13.3) (95% CI: -0.7-1.1)	2.3 (range: -3.4-13.3) (95% CI: 1.2-3.5)	-1.5 (range: -13.1-7.1) (95% CI: -2.8-(-0.3))
FO _c – FO _{pred} (%)	0.5	5.2	3.7
p values (FO _c – FO _{pred})	0.660	< 0.001	0.013
FO _{pred} using Equation (2) [0.39*FO _p +31.9] (mm)	---	48.0 (range: 41.3-54.9) (95% CI: 47.1-48.8)	---
FO _c – FO _{pred} (mm)	---	-0.2 (range: -7.5-10.5) (95% CI: -1.4-0.9)	---
FO _c – FO _{pred} (%)	---	0.5	---
p values (FO _{ct} – FO _{predicted})	---	0.689	---
FO _{pred} using Equation (3) [0.45*FO _p +25.4] (mm)	---	---	42.0 (range: 32.6-46.6) (95% CI: 41.1-42.8)
FO _c – FO _{pred} (mm)	---	---	-0.3 (range: -11.7-8.0) (95% CI: -1.5-0.9)
FO _c – FO _{pred} (%)	---	---	0.7
p values (FO _c – FO _{pred})	---	---	0.607

Table 4

Prediction of true femoral offset as measured on CT (FO_c) scans using regression equations for the entire group B, males and females. FO_{pred} was calculated using Equation (1, 2 and 3).

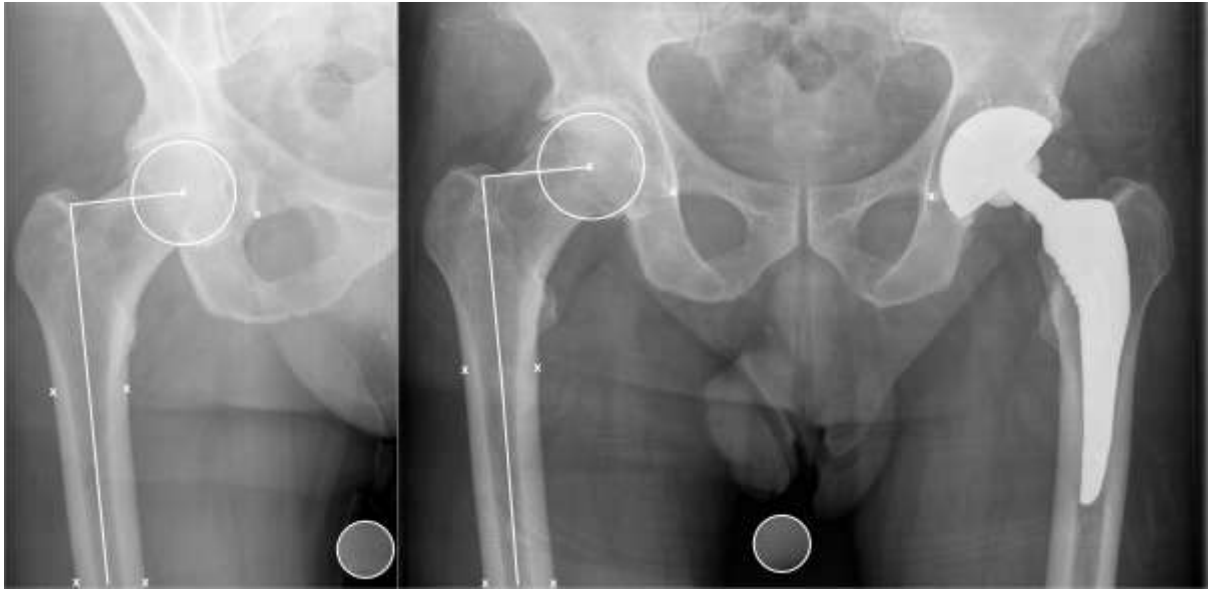


Figure 1: Radiographic measurements. Femoral offset (FO) measured on corresponding AP hip- and AP pelvis- radiographs for a male patient with primary osteoarthritis of the right hip. The difference between the two corresponding measurements was 5.1 mm.

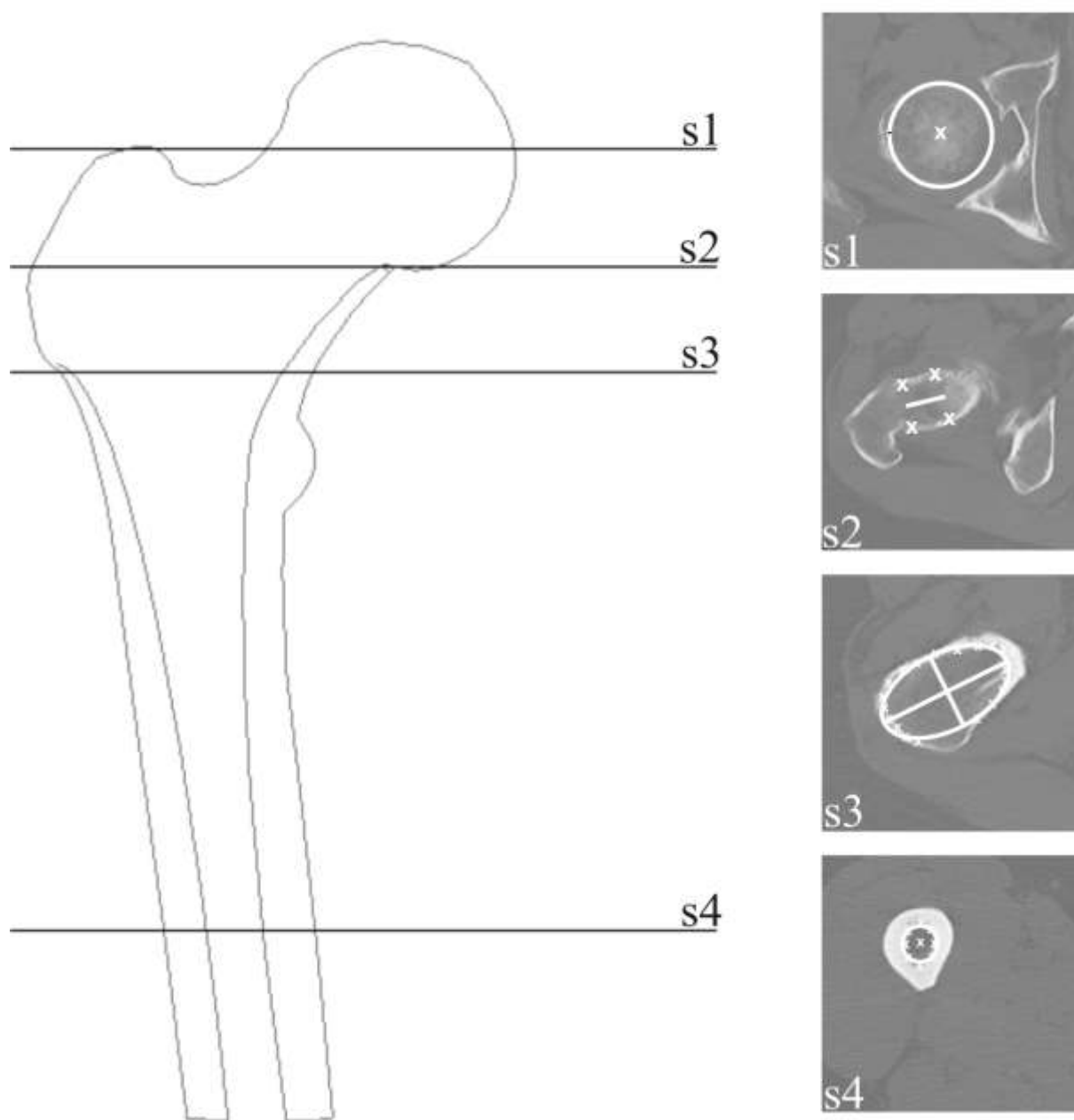


Figure 2: Selection of CT slices of the proximal femur for 3-D calculation of femoral offset (FO) and femoral anteversion (FA) based on CT: centre of the femoral head (s1), femoral neck axis (s2), centroid of the proximal femoral metaphysis (s3), centre of femoral isthmus (s4).

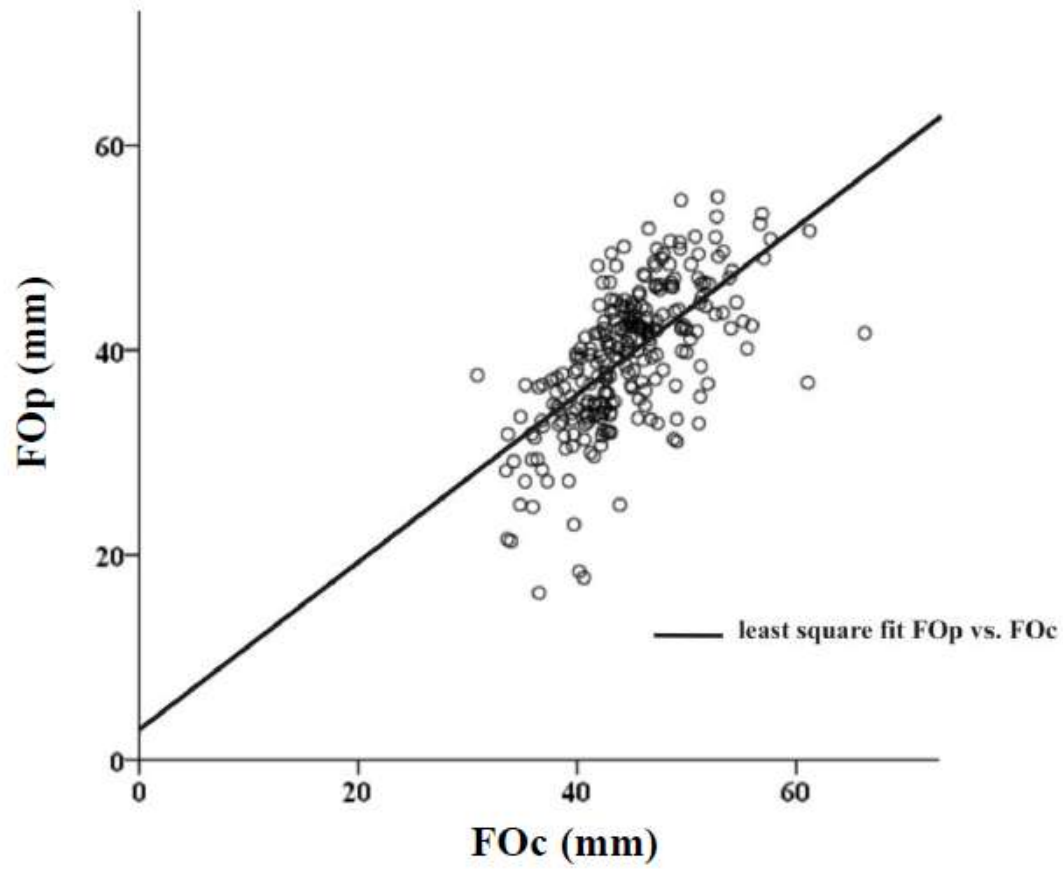


Figure 3: Group A: the scatter plot demonstrates a linear correlation between FOp(y-axis, mm) and FOc(x-axis, mm) ($r = 0.642$, $p < 0.001$). The line represents the least squares fit.

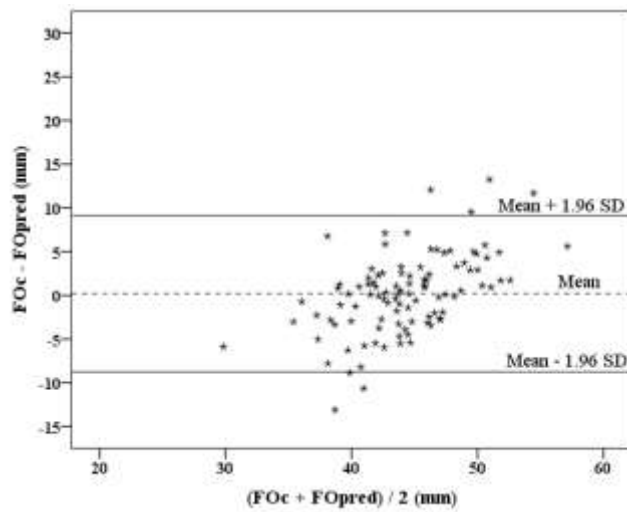
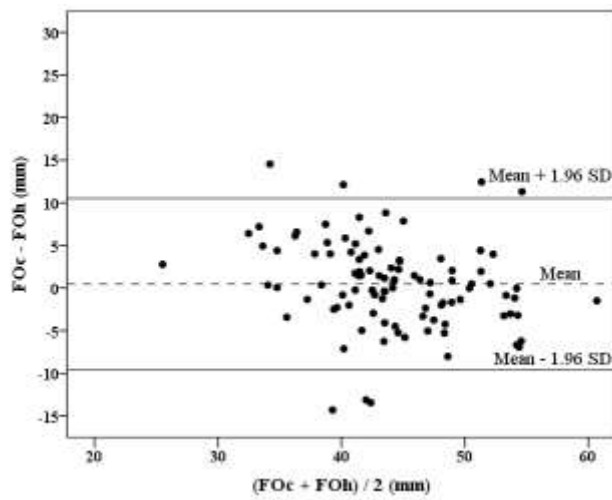
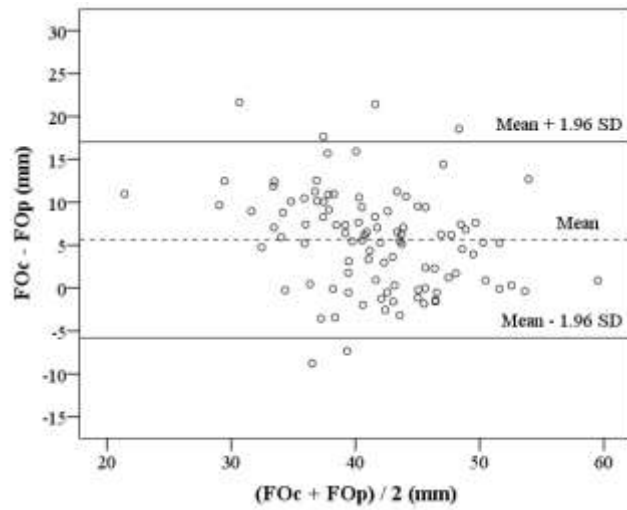


Figure 4: Bland–Altman plots illustrating the agreement in FO between CT and APpelvis radiographs (A: $FOc - FOp$), CT and AP hip radiographs (B: $FOc - FOh$), and CTand

predicted FO (C: $FO_c - FO_{pred}$) using Eq. (1). Values are given in mm with mean difference (mean) and standard deviation (SD).

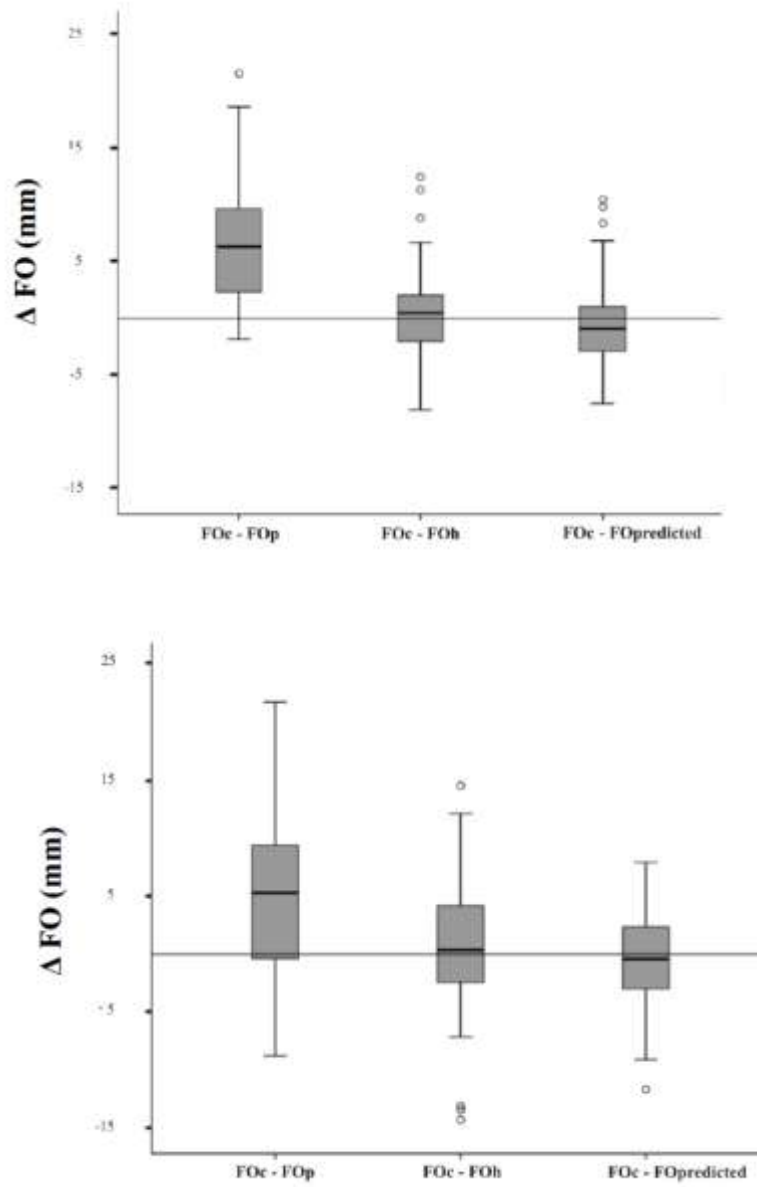


Figure 5: Differences (mm) in femoral offset (FO) between CT and AP pelvis radiographs($FO_c - FO_p$), CT and AP hip radiographs ($FO_c - FO_h$), and CT and FO_{pred} ($FO_c -$

FO_{pred}) for males (A) and females (B) using the gender specific equations as boxplots.