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Cross-Table Lateral Radiographs Accurately Predict Displacement in Valgus-Impacted Femoral Neck Fractures

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Background: Femoral neck fractures are classified as nondisplaced (Garden types I and II) or displaced (Garden types III and IV) on the basis of anteroposterior radiographs. Cross-table lateral radiographs are important in the assessment of Garden type-I and II fractures as posterior tilt of the femoral head may influence treatment results. A posterior tilt of >20° has been associated with an increased risk of treatment failure after internal fixation, although the precision of these measurements has not been validated. Therefore, the purpose of the present study was to compare cross-table lateral radiographs with 3-dimensional computed tomographic (3D-CT) reconstructions of Garden type-I and II femoral neck fractures.

Methods: Twenty-three patients presenting with Garden type-I and II femoral neck fractures that were verified on anteroposterior radiographs underwent CT scanning immediately after radiographic examination. 3D models of the fractured and uninjured femora were reconstructed from the CT images, and displacement of the 3D models was determined by superimposing the fractured and uninjured femora. We defined a coordinate system with its origin at the center of the uninjured femoral head with the x axis oriented medially; the y axis, posteriorly; and the z axis, cranially. Correlations between lateral radiographs and 3D models were assessed with the Spearman rank coefficient, mean difference, and limits of agreement.

Results: Posterior tilt of the femoral head on lateral radiographs was strongly correlated with displacement of the femoral head along the y axis of the 3D models, with a correlation coefficient of 0.86 ($p < 0.001$). Correlations between the findings on lateral radiographs and displacements along the x or z axis were weak, with coefficients of −0.30 ($p = 0.18$) and 0.21 ($p = 0.34$), respectively. The mean difference between displacement on lateral radiographs and displacement along the y axis of the 3D models was smaller, and demonstrated a smaller limits-of-agreement interval, compared with the x or z axis.

Conclusions: Our results demonstrated a strong correlation between posterior displacement of the femoral head on lateral radiographs and displacement along the y axis in 3D models of Garden type-I and II femoral neck fractures. This finding indicates that lateral radiographs provide an accurate assessment of posterior tilt.

Femoral neck fractures are classified as nondisplaced (Garden type I or II) or displaced (Garden type III or IV) on the basis of anteroposterior radiographs[1]. Garden type-I and II fractures are treated with internal fixation or arthroplasty, although guidelines vary between institutions. Cross-table lateral radiographs are important in the assessment of Garden type-I and II fractures as posterior tilt of the femoral head may influence the choice of implant. Angular measurements can be used to express the severity of posterior tilt, and previous findings have suggested that fractures with a posterior tilt of >20° are associated with an increased risk of treatment failure after internal fixation[2,3]. These angular measurements have been shown to be both reliable and independent of the position of the injured hip during radiographic examinations[2,4,5]; however, to our knowledge, the measurements have never been validated against a reference or gold standard despite their potential importance in the decision-making process.

Three-dimensional computed tomography (3D-CT) imaging has gained popularity as a diagnostic tool and also may improve the reliability of fracture classifications[6,7]. Furthermore, a recent study indicated that 3D-CT models describe the displacement of Garden type-I and II femoral neck fractures more

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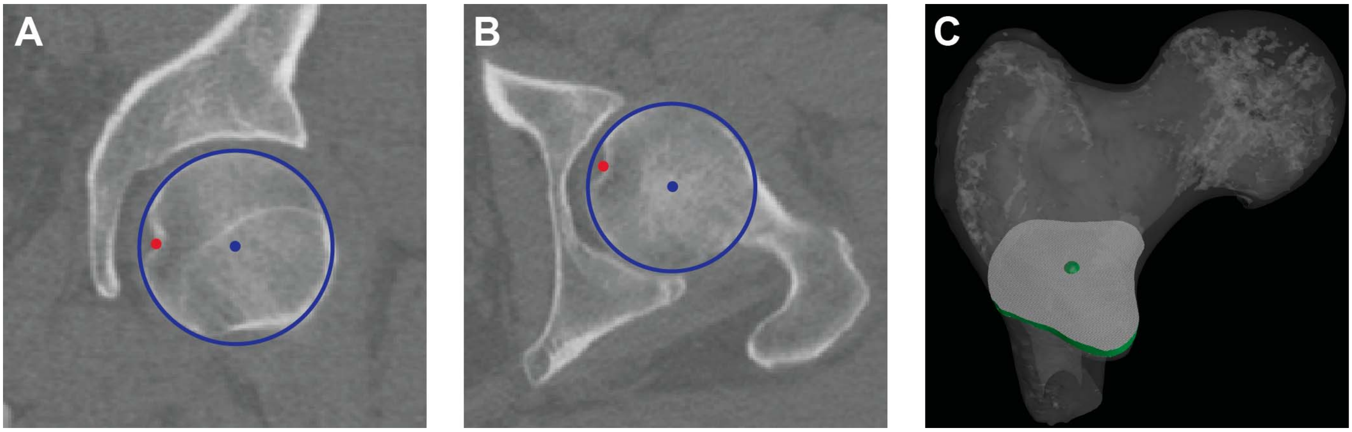

Fig. 1

Figs. 1-A and 1-B Coronal (**Fig. 1-A**) and axial (**Fig. 1-B**) CT scans of the hip. The red dot depicts the deepest point of the fovea, and the blue sphere indicates the surface of the femoral head. **Fig. 1-C** 3D model showing the center point (green dot) of the largest cross-sectional area of the lesser trochanter.

precisely than radiographs[8]. We recently demonstrated that 3D-CT models are both valid and reliable when used to evaluate linear displacement of the femoral head[9]. 3D models therefore can be used as a reference standard to validate lateral radiographs. On the basis of the findings from an experimental radiographic study with 3D-printed bone models[5], we hypothesized that the assessment of posterior tilt on lateral radiographs is accurate. The aim of the present study, therefore, was to determine whether lateral radiographs provide an accurate representation of posterior tilt and, thus, are valid for the assessment of Garden type-I and II femoral neck fractures.

Materials and Methods

All participants provided informed consent, and the study was approved by the Regional Committees for Medical and Health Research Ethics of Norway (reference 2014/2337) and by the data protection official at Akershus University Hospital (reference 15-048).

Inclusion

Between May 15, 2015, and February 16, 2016, the orthopaedic surgeon on call at Akershus University Hospital prospectively assessed anteroposterior and lateral radiographs of the hip that were made for patients who were admitted because of a suspected hip fracture. A consultant radiologist and a consultant orthopaedic surgeon subsequently reviewed the primary assessments. The anteroposterior and lateral radiographs were not standardized with respect to hip rotation during the examinations. Patients with an age of ≥70 years who presented with Garden type-I and II femoral neck fractures were eligible for inclusion in the present study, and patients were given written and verbal information about the purpose and procedures of the study by the surgeon on call before providing consent. Patients with previous injuries to the hip, hip implants, malignant disease, deformities, osteoarthritis (Kellgren and Lawrence grade 2 or higher)[10], or osteomyelitis and those who were unable to provide informed consent were excluded from the study.

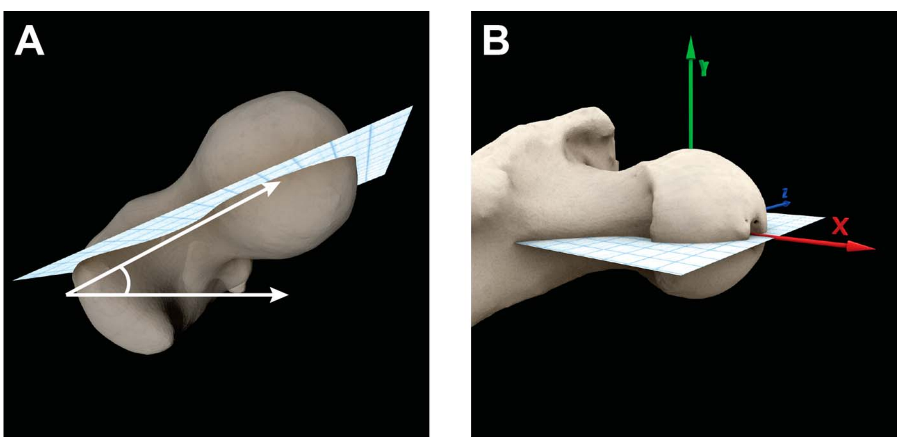

Fig. 2

Figs. 2-A and 2-B 3D models of the femoral head. **Fig. 2-A** The orientation of the analytical plane approximates the femoral anteversion angle. **Fig. 2-B** The origin of the coordinate system is defined at the center of the uninjured femoral head. The x axis crosses the center of the fovea, the y axis is oriented in a posterior direction, and the z axis is oriented cranially.

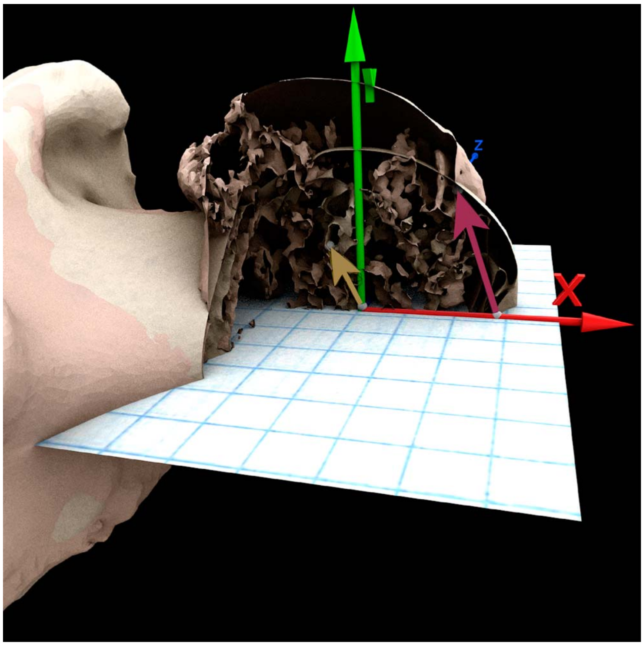

Fig. 3

3D model showing the fractured femur (pink) superimposed on the uninjured femur (white). The tan arrow depicts the vector between the centers of the 2 femoral heads, and the purple arrow represents the vector between the 2 foveae.

Patients who were unable to undergo CT scans after the radiographic examinations also were excluded in order to prevent delay of surgical treatment. CT images were compared with the radiographs to account for the possibility of secondary displacement between radiographic examinations and CT scans. Of the 26 eligible patients, 1 patient was excluded because of the occurrence of secondary displacement between the radiographic examination and the CT scan, 1 patient was excluded because of the presence of an orthopaedic implant in the contralateral hip, and 1 patient was excluded because the primary classification was incorrect. The study included 23 patients (16 female and 7 male) with a median age of 83 years (range, 70 to 95 years). Nine fractures were on the left side.

Generation and Alignment of the 3D Models

CT examinations were conducted with an iCT 256-slice CT scanner (Philips) set to 120 kVp and 60 mA with 512 × 512-pixel image resolution, 0.78-mm pixel size, 0.45-mm slice increment, and 0.9-mm slice thickness. Images were then exported to Mimics (version 18; Materialise) in DICOM (Digital Imaging and Communications in Medicine) format for further processing. For segmentation, the threshold was set to 1,250 to 2,600 Hounsfield units (HU). The resulting models were sliced at the base of the femoral neck and 5 cm below the lesser trochanter, leaving only the trochanteric region of the proximal part of the femur. A mirrored model of the femoral neck fracture was exported together with the model of the uninjured proximal part of the femur to 3-matic (version 18; Materialise). The models of the femoral neck fracture and the uninjured femur were then superimposed by means of point set registration. To achieve the best possible alignment, the computer software used an iterative closest point (ICP) algorithm to minimize the distance between corresponding points. This process requires manual input of at least 3 corresponding regions on the 2 models, and, to improve the precision of the ICP alignment, we used 7 anatomical landmarks as previously described[8].

Radiographic Assessments

A consultant orthopaedic surgeon reviewed the CT scans. The center of the fovea was identified by its deepest point, and the center of the femoral head was determined by drawing a sphere tangential to its cortical contour (Figs. 1-A and 1-B). The computer software calculated the cross-sectional area of different segments at the height of the lesser trochanter, and the center of the lesser trochanter was defined by the midpoint of the cross-section with the largest area (Fig. 1-C).

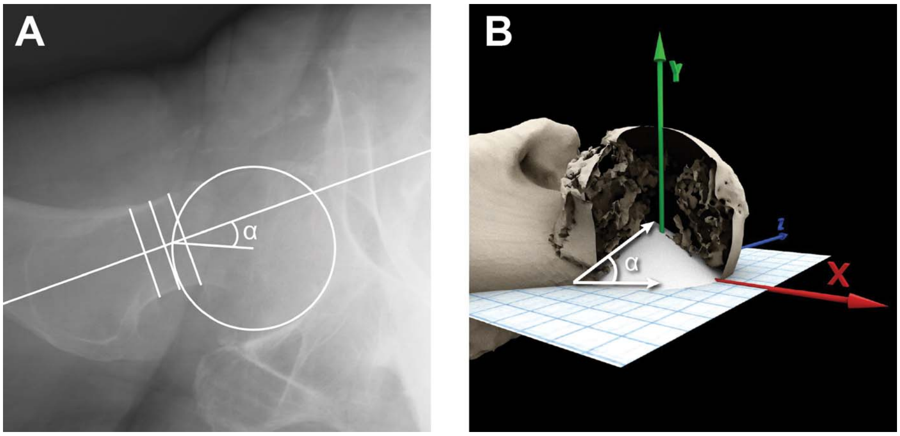

Fig. 4

Fig. 4-A Cross-table lateral radiograph illustrating the measurement of posterior tilt as described by Palm et al.[2]. The intersection between the femoral head and the analytical plane forms a cone with its apex at the center of the femoral head. **Fig. 4-B** Corresponding 3D model. The angle at the base of the cone can be considered equivalent to the 2D posterior tilt angle.

TABLE I Rotations and Displacements of the Femoral Head on Cross-Table Lateral Radiographs and 3D Models of Nondisplaced (Garden Type-I and II) Femoral Neck Fractures*

	Mean (95% CI)	Range
Posterior tilt *(deg)*		
On lateral radiographs	14.1 (9.8 to 18.3)	−4.7 to 31.0
On 3D models	11.7 (7.8 to 15.5)	−4.0 to 28.2
Rotation of femoral head *(deg)*	18.3 (14.7 to 22.0)	4.6 to 38.3
Displacement of femoral head *(mm)*		
Absolute displacement	9.6 (7.9 to 11.3)	3.0 to 15.7
Displacement along x axis	−0.7 (−3.5 to 2.0)	−12.0 to 8.6
Displacement along y axis	5.1 (3.3 to 6.9)	−1.5 to 13.2
Displacement along z axis	4.5 (3.4 to 5.6)	0.6 to 11.0

*CI = confidence interval.

TABLE II Correlations Between Posterior Tilt Assessed by Cross-Table Lateral Radiographs and 3D Models of the Corresponding Nondisplaced (Garden Type-I and II) Femoral Neck Fractures

	Spearman ρ	P Value
Mean posterior tilt in 3D models	0.86	<0.001
Rotation of femoral head	0.31	0.15
Displacement of femoral head		
Absolute displacement	0.60	0.02
Displacement along the x axis	−0.30	0.18
Displacement along the y axis	0.86	<0.001
Displacement along the z axis	0.21	0.34

Reference Points, Reference Plane, and Coordinate System

The centers of the fovea, femoral head, and lesser trochanter were represented as single points in a 3D space, and together they defined an analytical plane that nearly aligned with the femoral anteversion angle (Fig. 2-A). The position of the analytical plane was based on the uninjured femur, and we defined a coordinate system with its origin at the center of the uninjured femoral head. A vector running from the center of the femoral head through the center of the fovea defined the x axis, and the y axis was oriented perpendicular to the plane in a posterior direction. The z axis ran parallel to the plane in a cranial direction (Fig. 2-B). The distance between 2 points was defined by the magnitude of a vector connecting the 2 points (Fig. 3). Femoral head rotation was defined by a vector running from the center of the femoral head to the center of the fovea, and differences in rotation were determined by calculating the absolute angle between corresponding vectors.

Angular Measurements of Posterior Tilt

Posterior tilt of the femoral head was measured with mdesk software (RSA Medical) according to the method described by Palm et al.[2] (Fig. 4-A). To calculate a 3D analogue of the posterior tilt angle, we drew a sphere tangential to the femoral head of the fracture model. The resulting intersection between the sphere and the analytical plane formed a cone with its apex at the center of the injured femoral head. The angle at the base of the cone can be considered equivalent to the 2-dimensional (2D) posterior tilt angle (Fig. 4-B).

Outcomes

The primary outcome was the correlation between posterior tilt on lateral radiographs and displacement along the y axis of the corresponding 3D model. We assessed correlations by calculating the Spearman rank correlation coefficient, which, in comparison with the Pearson coefficient, is more robust to skewed data and outliers[11]. It is generally accepted that a coefficient of >0.7 indicates a strong linear relationship[12]. Secondary outcomes were the correlation between posterior tilt on lateral radiographs and the 3D analogue of the posterior tilt angle and mean differences between displacement on lateral radiographs and displacement along the x, y, and z axes of the 3D models.

Statistical Analysis

Normality was assessed by the inspection of histograms. Limits of agreement define an interval within which 95% of the

TABLE III Correlations Between Displacement Along the X, Y, and Z Axes in 3D Models of Nondisplaced (Garden Type-I and II) Femoral Neck Fractures

	Spearman ρ	P Value
X axis versus y axis	−0.24	0.27
X axis versus z axis	0.44	0.04
Y axis versus z axis	0.35	0.11

TABLE IV Mean Difference Between Posterior Displacement on Cross-Table Lateral Radiographs and Displacement on 3D Models of Corresponding Nondisplaced (Garden Type-I and II) Femoral Neck Fractures, with Limits of Agreement*

Displacement of Femoral Head	Mean Difference	Limits of Agreement
Absolute displacement	−18.3	−50.9 to 14.4
Displacement along x axis	24.4	−36.6 to 85.4
Displacement along y axis	0.5	−22.5 to 23.4
Displacement along z axis	2.9	−31.0 to 36.7

*Displacement is divided by the radius of the femoral head and is expressed as a percentage in order to create comparable units of measurements.

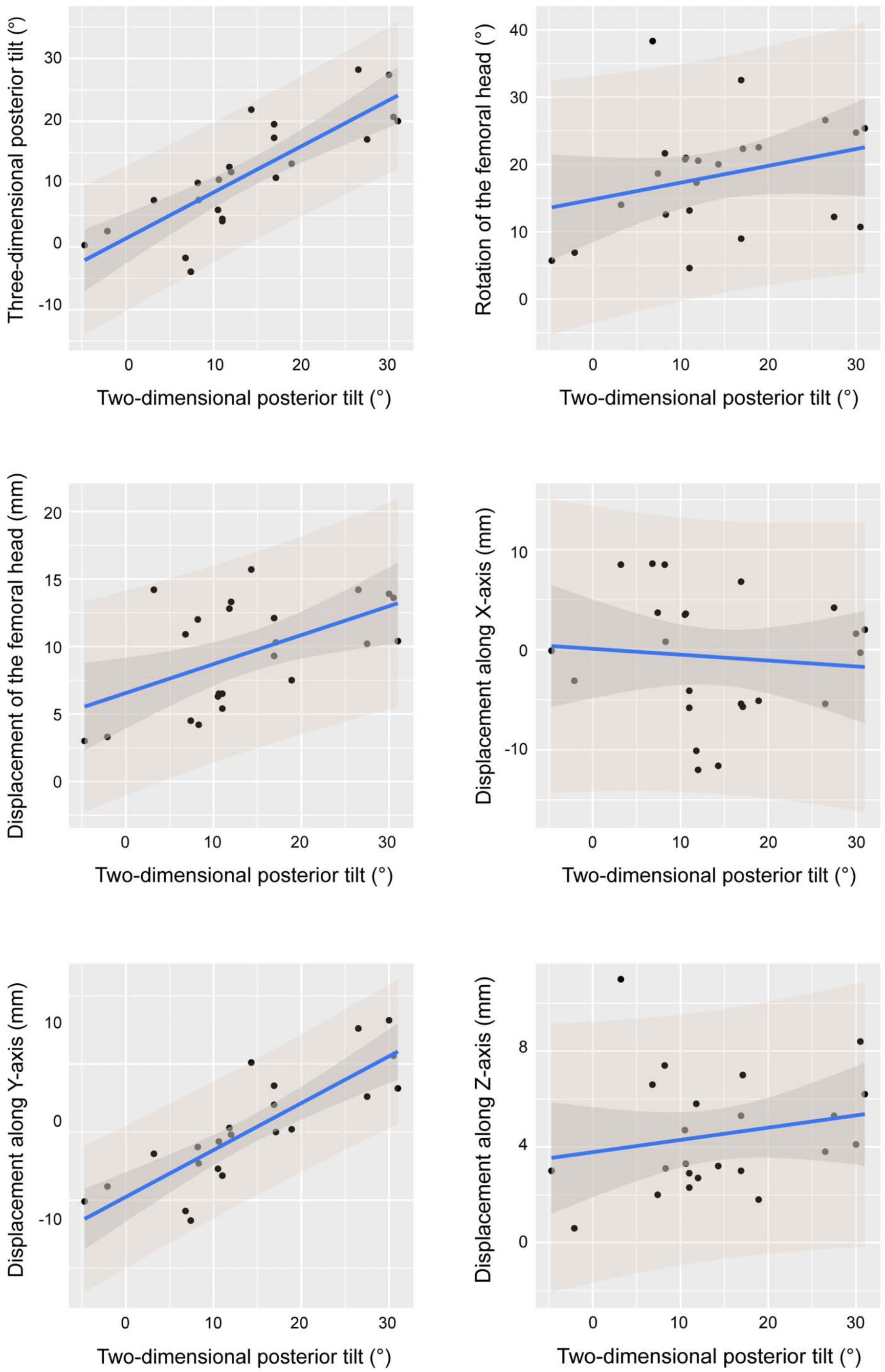

Fig. 5
Scatterplots of posterior tilt on lateral radiographs and displacement of 3D models. The 95% confidence intervals are shown in dark gray, and the 95% prediction intervals are shown in light gray.

differences will fall when 2 measurements are compared. Posterior displacement on lateral radiographs was calculated by measuring the distance from the center of the femoral head to a line bisecting the femoral neck (Fig. 4-A). However, the lateral radiographs were not calibrated, and distances could not be measured directly. To create comparable units of measurement for calculations of mean difference and limits of agreement, we chose to express displacement as a ratio of the distance divided by the femoral head radius. Similarly, for calculations of mean difference and limits of agreement, we also expressed absolute displacement and displacement along the x, y, and z axes of the 3D models as a ratio of the displacement divided by the femoral

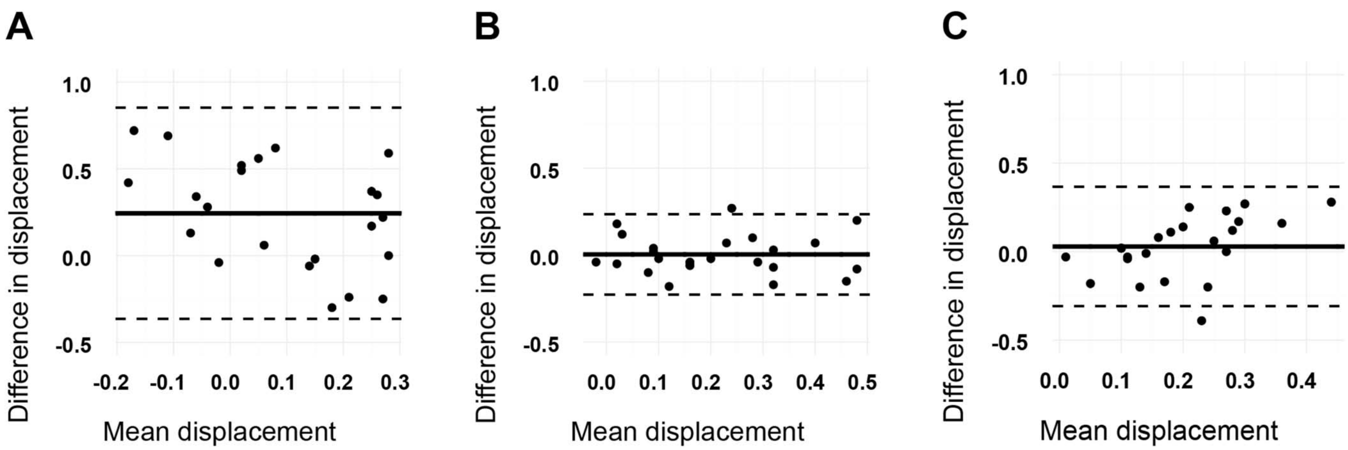

Fig. 6

Bland-Altman plots comparing displacement on cross-table lateral radiographs with the displacement of 3D models along the x axis (**Fig. 6-A**), y axis (**Fig. 6-B**), and z axis (**Fig. 6-C**). Displacement was expressed as a ratio relative to the femoral head radius.

head radius. Calculations of limits of agreement were performed with the R package *BlandAltmanLeh*[13].

Femoral offset was determined by measuring the distance from the center of the femoral head to a line bisecting the long axis of the femur on anteroposterior radiographs. Femoral offset and displacement along the x axis were expressed as ratios relative to the femoral head radius, and the correlation between femoral offset and displacement along the x axis of the corresponding 3D model was evaluated with the Spearman rank correlation coefficient.

Prediction intervals, 95% confidence intervals of the mean, and scatterplots were generated in the R package *ggplot2*[14]. The prediction interval represents an interval that contains the next measured value with 95% certainty. Bland-Altman plots were used to assess agreement between 2 different measurements. All statistical analyses were performed in R (version 3.3.3 for Mac OS X; R Foundation for Statistical Computing)[15].

Sample size calculations were based on the hypothesis that the correlation coefficient for displacement on lateral radiographs and displacement on 3D models was >0.7. With a 2-tailed alpha value of 0.5 and with 95% power, the required sample size was 20 patients[16].

Results

Mean values for measurements of posterior tilt on lateral radiographs and for rotation and linear displacement of the femoral head on 3D models are given in Table I. Posterior tilt on lateral radiographs correlated strongly with displacement of the femoral head along the y axis and with the 3D analogue of posterior tilt measurements. The correlation between posterior tilt on lateral radiographs and absolute displacement of the femoral head was also significant, but with a lower correlation coefficient (Table II). Correlations between displacements along the x, y, and z axes are given in Table III. There was no correlation between femoral offset on anteroposterior radiographs and displacement along the x axis of the corresponding 3D models, and the correlation coefficient was 0.01 ($p = 0.96$).

The mean difference in linear displacement was smallest between displacement on lateral radiographs and displacement along the y axis of the 3D models (Table IV). Scatterplots of posterior tilt on lateral radiographs versus displacement of 3D models revealed a similar trend, with a linear correlation between posterior tilt and displacement along the y axis. The resulting prediction and confidence intervals also were smaller for the correlation between posterior tilt and displacement along the y axis as compared with displacement along the x or z axis (Fig. 5). Agreement between displacement on lateral radiographs and displacement of 3D models was also assessed with Bland-Altman plots (Fig. 6).

Discussion

We hypothesized that lateral radiographs accurately assess posterior tilt of the femoral head in patients with Garden type-I and II femoral neck fractures. Our findings demonstrated a strong correlation between posterior tilt on lateral radiographs and posterior displacement on the corresponding 3D models.

Posterior tilt or the presence of valgus impaction was indicated by displacement along the y or z axis, respectively. The mean displacement of the 3D models was largest along the y axis, followed by displacement along the z axis. However, there was no correlation between posterior tilt on lateral radiographs and displacement along the z axis, suggesting that valgus impaction is not necessarily associated with posterior tilt of the femoral head. The radiographs were not standardized with respect to the position of the hip during the examinations, and there was no correlation between femoral offset on the anteroposterior radiograph and displacement along the x axis. This finding suggests that measurements of posterior tilt, as opposed to femoral offset, are more robust to variations in the position of the hip during radiographic examinations.

The trial had several limitations, the most important being sample size. Although the number of patients satisfied the a priori sample power analysis, a larger study may be necessary to account for discrepancies and anatomical variations in the general population. Asymmetrical anatomical variations may influence the accuracy of 3D-CT-based measurements as these measurements

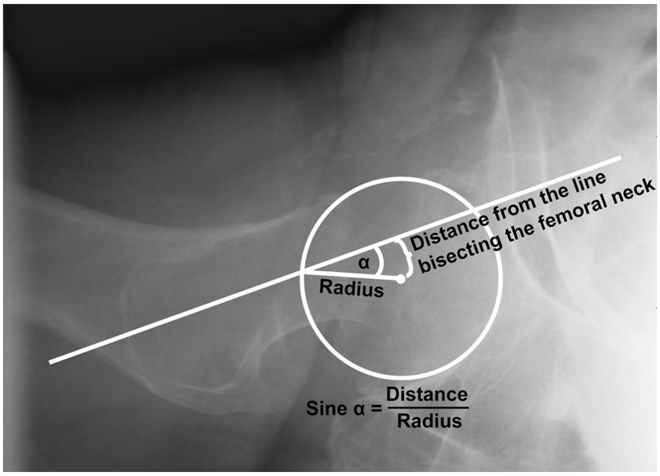

Fig. 7

Radiograph illustrating the method used to calculate posterior tilt. The mean difference and limits of agreement were calculated by measuring the distance from a line bisecting the femoral neck to the center of the femoral head. Displacement was expressed as a ratio of the distance divided by the radius of the femoral head.

rely on the uninjured hip being identical to the injured hip prior to the fracture. Although side-to-side variations were found to be minor in a previous investigation of uninjured hips, that study included a limited number of patients[9]. In the present study, CT scans and radiographic examinations were conducted at different time points. To minimize the risk of secondary displacement, we conducted CT scans shortly after the presence of a Garden type-I or II fracture was confirmed on anteroposterior radiographs. CT images were compared with the corresponding radiographs, but minor changes are difficult to evaluate and we cannot exclude the possibility of a change occurring between CT scans and radiographic examinations. We also did not assess the reliability of the measurements used in the present study, but we previously evaluated both test-retest and intertester reliability of these measurements[4,9]. The measurements were all found to be acceptable, with the exception of femoral head rotation in 3D models[9]. Nonetheless, we chose to include rotational measurements to allow for comparison with the findings of similar studies. Importantly, lateral radiographs were not standardized with respect to the position of the injured hip during examinations, and flexion and rotation of the hip could influence assessments of posterior tilt on lateral radiographs. However, in a recent study, we found that the influence of flexion and rotation of the hip is negligible in positions that are normally present during radiographic examinations[5]. Furthermore, we did not conduct lateral radiographic examinations of the uninjured contralateral hip, which would have caused patient discomfort and possibly would have risked secondary displacement. Assessments of posterior tilt on 3D models were, however, based on the contralateral hip. Comparison of 3D models with radiographs of both the injured and contralateral hips therefore may potentially alter the strength of the correlation.

We chose to replace angular measurements with a ratio that was calculated by dividing linear displacement by the radius of the femoral head. The purpose was to create identical units of measurements for calculating agreement and limits-of-agreement intervals. To replace an angular measurement with a ratio lacking units may seem arbitrary, but measurements of posterior tilt on lateral radiographs are derived from the sine of the exact same ratio (Fig. 7). Thus, posterior tilt describes linear displacement, and not the rotation of the femoral head as misleadingly implied by its unit of measurement.

The influence of preoperative posterior tilt on treatment results after internal fixation has been debated. Two studies have indicated that a posterior tilt of >20° is associated with an increased risk of fixation failure[2,3], but those findings have been contested by the authors of a third study[17]. The conflicting results could possibly be explained by measurements having poor reliability, but the reliability has been reported to be moderate to excellent[2,4]. It is therefore unlikely that low reliability is the cause of the observed inconsistencies, which underlines the importance of determining the validity of the measurements. Our findings demonstrate a strong correlation between posterior tilt evaluated on lateral radiographs and posterior displacement on 3D models of the corresponding femoral neck fracture. This strong correlation indicates that lateral radiographs correctly portray displacement. The conflicting reports could, alternatively, be explained by selection bias, as 2 of the 3 studies in question were retrospective cohort studies. Fractures and posterior tilt were furthermore categorized differently, leaving the possibility of assessment bias.

Our results demonstrated a strong correlation between posterior tilt of the femoral head on cross-table lateral radiographs and posterior displacement of the femoral head on 3D models of the corresponding Garden type-I or II femoral neck fracture. Our study confirms that lateral radiographs accurately assess posterior tilt in patients with Garden type-I and II femoral neck fractures. ■

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