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Original article

Effect of Combined Flexion and External Rotation on Measurements of the Proximal Femur from Anteroposterior Pelvic Radiographs*

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ABSTRACT

Introduction: Fixed flexion and external rotation contractures are common in patients with hip osteoarthritis and in particular before total hip replacement (THR). We aimed to answer the following question: how does combined flexion and external rotation of the femur influence the radiographic assessment of 1) femoral offset (FO) 2) neck-shaft angle (NSA) and 3) distance (parallel to the femoral axis) from greater trochanter to femoral head centre (GT-FHC)?

Hypothesis: Combined flexion and external rotation impact the accuracy of two-dimensional (2D) proximal femur measurements.

Materials and methods: Three-dimensional (3D) CT segmentations of the right femur from 30 male and 42 female subjects were acquired and used to build a statistical shape model. A cohort (n = 100; M:F = 50:50) of shapes was generated using the model. Each 3D femur was subjected to external rotation (0° – 50°) followed by flexion (0° – 50°) in 10° increments. Simulated radiographs of each femur in these orientations were produced. Measurements of FO, NSA and GT-FHC were automatically taken on the 2D images.

Results: Combined rotations influenced the measurement of FO (p<0.05), NSA (p<0.001) and GT-FHC (p<0.001). Femoral offset was affected predominantly by external rotation (19.8 ± 2.6 mm [12.2 to 26.1 mm] underestimated at 50°); added flexion in combined rotations only slightly impacted measurement error (20.7 ± 3.1 mm [13.2 to 28.8 mm] underestimated at 50° combined). Neck-shaft angle was reduced with flexion when external rotation was low (9.5 ± 2.1° [4.4 to 14.2°] underestimated at 0° external and 50° flexion) and increased with flexion when external rotation was high (24.4 ± 3.9° [15.7 to 31.9°] overestimated at 50° external and 50° flexion). Femoral head centre was above GT by 17.0 ± 3.4 mm [3.9 to 22.1 mm] at 50° external and 50° flexion. In contrast, in neutral rotation, FHC was 12.2 ± 3.4 mm [3.9 to 22.1 mm] below GT.
**Discussion:** This investigation adds to current understanding of the effect of femoral orientation on preoperative planning measurements through the study of combined rotations (as opposed to single-axis). Planning measurements are shown to be significantly affected by flexion, external rotation, and their interaction.

**Level of Evidence:** IV Biomechanical study

**Keywords:** femoral orientation, preoperative planning, femoral offset, neck-shaft angle
1. Introduction

Reconstruction of femoral geometry, in particular femoral head centre (FHC), is an important consideration in total hip replacement (THR). The FHC location impacts function, quality of life, abductor strength, range of motion, leg length, and implant survival [1–4]. Two-dimensional (2D) radiographic assessment of the proximal femur has been standard for preoperative planning of THR, predominantly using the anteroposterior radiograph [5]. Three-dimensional (3D) planning (based on computed tomography, CT) has shown better accuracy [6,7] but remains non-routine due to additional radiation exposure to the patient and increased cost. A key issue with 2D planning is uncertain 3D orientation of the femur [8,9].

External rotation of the femur has been highlighted as an important source of error for the measurement of both femoral offset (FO) [10] and neck-shaft angle (NSA) [11]. However, many studies exclude the impact of flexion [10,11]. Olsen et al. [12] reported considerable errors in radiographic NSA when either external rotation or flexion were present for a single synthetic femur. A detailed review of radiographic NSA highlighted variability in the measurement and that correction methods adjust for femoral neck version/rotation only, i.e. the potential influence of combined rotation is excluded [13]. To the best of the authors’ knowledge, no group has explicitly examined the relationships between combined rotation and preoperative measurements.

This investigation aimed to answer the following questions: how does combined flexion and external rotation of the femur influence the radiographic assessment of 1) femoral offset (FO) 2) neck-shaft angle (NSA) and 3) distance (parallel to the femoral axis) from greater trochanter to femoral head centre (GT-FHC)? The working hypothesis was that combined rotations would affect the validity of these measurements on 2D radiographic images.

2. Material and methods

2.1 Dataset of femoral shapes
The Virtual Skeleton Database (SICAS, Swiss Institute for Computer Assisted Surgery, Switzerland) [14] was used to acquire CT segmentations for male (n = 30) and female (n = 42) femora. Separate statistical shape models were constructed for the male and female groups using Scalismo (R0.12, Graphics and Vision Research Group, University of Basel, Switzerland) [14]. The model was built by rigid alignment of the CT segmented shapes and non-rigid registration of a reference shape followed by a principal component analysis to identify the main directions of variation in femoral shape. This provided a parametric model of shape with the ability to generate femoral shapes, each with their points ordered in an identical manner [15]. This facilitated automatic measurement of variables on 2D images, without which this study would be infeasible (>10,000 measurements required).

A sample of virtual femoral shapes (n = 100; M:F = 50:50) was generated from the male and female shape models. The first 10 modes of the shape models were used, covering 96% and 98% of the shape variance in the training set for males and females respectively. Shape parameters were randomly generated in a normal distribution and limited to ± 3 standard deviations from the mean.

2.2 Femoral orientation

Head, neck, and proximal shaft regions were identified on the mean shape (Figures legend Figure 1) using MATLAB (R2015b, The MathWorks, Inc., MA, USA). The femoral shaft axis was then defined by points P₃ and P₄ (the mean of the points in the upper and lower shaft regions; Figure 1). The FHC (P₁) was determined using a sphere-fit function on points in the head region (Figure 1). Femora were neutralised by aligning the plane formed by P₁, P₃ and P₄ with the X-Z plane (coronal plane) of the coordinate frame (Figures legend Figure 1B). Each shape was translated so that the FHC was coincident with the origin. The femoral shapes were assigned an external rotation followed by flexion rotation. External
rotation and flexion each ranged from 0° to 50° (in 10° increments) allowing for 36 unique orientations.

2.3 Simulated radiographs

Each rotated instance was then used to generate a simulated radiograph in MATLAB; the process for this has been described previously [16]. Briefly, vectors joining each 3D point on the surface of the rotated femur to an origin point (representing the X-ray source) were calculated, the intersection of each vector with a plane (representing the X-ray detector plane) then became the 3D point’s 2D projection. The source-to-detector distance was 1.2 m and the FHC was offset from the central beam by 90 mm, in line with the clinical practice of directing the central beam to the pubic symphysis. Magnification was corrected for based on the ratio of the distances from the source to the centre of the femoral head and from the source to the detector plane (1.2 in all cases). Since the projected points retained the same order for all shapes, regions could be identified and measurements automatically taken (Figures legend Figure 1). The 2D location for the FHC was calculated by the circle-fit function in MATLAB using the boundary points of the head region (Figures legend Figure 1 and Figure 2). Femoral offset was measured then by constructing the 2D femoral axis from the projections of points P3 and P4 and then calculating the distance from this axis to the FHC (Figures legend Figure 1 and Figure 2). The neck axis was constructed from the projection of P1 and P2 and the angle between this axis and the femoral shaft axis was defined as the NSA (Figures legend Figure 1 and Figure 2). The tip of greater trochanter was identified as the most superior of the projected points excluding head and neck regions (Figures legend Figure 1). A line perpendicular to the femoral shaft axis and through the tip of greater trochanter was then constructed and the perpendicular distance from it to femoral head centre (GT-FHC) was measured (Figure 2). If FHC was below GT, it was assigned a negative sign,
and a positive sign if above. In total, 10,800 measurements were taken on 3,600 simulated radiographs representing 100 femora in 36 unique rotations, highlighting a major benefit of a computational approach as opposed to *in-vivo* or *in-vitro* methods.

### 2.4 Statistical analysis

Data was analysed using the R statistical software environment [17]. Linear mixed-effects models were used for statistical analysis; the *lme4* package was used for model fitting [18]. These models mix factors that affect the mean (fixed effects) and factors that affect the variability only (random effects) allowing for the contribution of unknown patient-specific differences to be quantified via the femur ID. Separate models were fitted for FO, NSA and GT-FHC measurements as the dependent variables. In all cases fixed effects were external rotation, flexion, their interaction, and sex, while the random effect was the femur ID (a dummy variable coded from 1–100). The model allowed for a different intercept for each subject. The *MuMIn* [19] package was used to calculate $R^2$ values for both fixed effects (marginal $R^2$, hereafter denoted by $R^2_m$) and the overall model including random effects (conditional $R^2$, hereafter denoted by $R^2_c$). Interaction plots were produced using the *sjPlot* [20] package and presented for significant (p<0.05) interaction terms.

3. Results

As expected, apparent FO was extremely sensitive to external rotation (Figure 3A), decreasing by 4.3 mm for every added 10° (p<0.001) of external rotation (at zero flexion). In contrast, FO was decreased by just 0.1 ± 0.03 mm per 10° flexion (p<0.001) (at zero external rotation), a relationship which was relatively unaffected (in terms of magnitude) by the level of external rotation. This is visualised in Figure 4, which shows 0° and 30° level of external rotation respectively with little difference in the appearance of FO.
The measurement of NSA in 2D was more sensitive than FO to combined flexion and external rotation, evident from the difference in coefficients (Table 1) and in slopes on the interaction plot (Figure 3C). At low values (<10°) of external rotation, flexion tended to lower the NSA value (Figure 4) while the opposite was true for high values (>30°) of external rotation (i.e. NSA angle appeared larger with increased flexion) (Figure 4). Flexion, when external rotation was neutral, had the effect of decreasing the NSA measurement on simulated radiographs by 1.6 ± 0.03° per 10° of flexion (p<0.001; Figure 4). Conversely, at zero flexion the apparent NSA increased by 2.6 ± 0.03° per 10° of external rotation (p<0.001; Figure 4).

Assessment of GT-FHC in 2D was relatively insensitive to external rotation or flexion alone, provided the femur was neutral in either axis; the measurement was increased by 0.3 ± 0.03 mm per 10° external rotation (p<0.001; Figure 4) (at neutral flexion) and by 0.1 ± 0.03 mm per 10° flexion (p<0.001; Figure 4) (at neutral external rotation). There were, however, large deviations from the true measurement when flexion and external rotation were combined, with GT-FHC value always increasing (Figure 4).

There were some differences, independent of rotation, between the sexes. Male subjects had a larger FO measurement by 2.9 ± 0.9 mm (p<0.001) and a lower NSA by 1.5 ± 0.7° (p<0.05) (Figure 5). Detailed information on the statistical analysis is presented in (Table 1). Significant interaction terms meant that the effect of flexion or external rotation could not be assessed in isolation i.e. the effect of external rotation on a measurement must also include the level of flexion and vice versa (Figure 6) (Electronic supplement annex).

4. Discussion

Previous experiments and correcting factors have focussed on the effect of single-axis rotations (external rotation or flexion) on the appearance of preoperative planning measurements [10–
This investigation has shown that combined rotations have a considerable effect on the radiographic appearance of FO, NSA and GT-FHC, influencing the surgeon’s ability to correctly assess the patient’s anatomy and, in particular, the level of neck resection. Preoperative planning, as well as determining the size of the femoral component, aids in the restoration of FHC (which is primarily determined by the level of neck resection). Restoration of FHC contributes to function, quality of life, abductor strength, range of motion, leg length, and implant survival [1–4]. Considerable reductions in FO with external rotation presented in this study are in good agreement with previous works [10]. In addition, this work has shown a negligible effect of flexion on the measurement of FO.

Olsen et al. [12] and Kay et al. [11] showed similar trends for the measurement of NSA when the femur was rotated (i.e. external rotation increasing NSA while flexion decreased NSA), although combined rotations were not examined.

The GT-FHC distance has shown a wide variation in the clinic [21] compared to the neutral measurements in this study, suggesting that combined rotations may be influencing the variable.

The main limitations of this study were i) the measurements were taken automatically, meaning manual measurement error is not represented; ii) magnification errors were corrected but the variation in phantom placement was not modelled; and iii) noise of the X-ray image was not included. However, neglecting these issues allowed analysis of the error produced directly from orientation, independent of other inaccuracies (which would be expected to be distributed symmetrically around the mean).

5. Conclusion

Combined rotations can cause large deviations from the neutral measurement for FO, NSA and GT-FHC. Consequently, caution is advised in interpreting preoperative planning measurements.
from AP pelvic radiographs, particularly when FO is low, NSA is high and greater trochanter appears distal to the FHC.

Ethical approval: Anonymised Imaging data was provided under a creative commons license (CC BY-NC-SA) by the Swiss Medical Image Repository. Data acquisition was fully anonymized and controlled by a governmental data protection agency (Datenschutzbeauftragter Stadt Bremen, Bremen, Germany).

Conflict of interest: Related to the current study, Nicholas Dunne, Alex Lennon and John O’Connor report grants from Belfast Arthroplasty Research Trust and from Department of Employment and Learning, Northern Ireland. Megan Rutherford reports grants from Belfast Arthroplasty Research Trust related to the current study. Janet Hill and David Beverland have no conflict to disclose.

References


Table 1: Results of statistical analyses showing coefficients ($B$) of the fixed parts of the mixed effects models, 95% confidence intervals ($CI$), $p$-value ($p$), marginal $R_m^2$, and conditional $R_c^2$. Female was the reference level for gender and, as such, “Sex (male)” is only included for male subjects.

<table>
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<th>GT-FHC</th>
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<td>$CI$</td>
<td>$p$</td>
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Figures legend

Figure 1: Views from the anteroposterior (A) and mediolateral (B) direction of the head, neck and proximal shaft regions identified on the mean shape. The mediolateral view (B) shows the neutral alignment of the femur in both rotation and flexion axes.

Figure 2: Measurements taken on simulated radiographs: GT-FHC, FO and NSA

Figure 3: Interaction plots showing the relationship between flexion and the predicted value (95% confidence interval) of the fitted models for FO (A), NSA (B) and GT-FHC (C) at different levels of external rotation. Differences in slope between lines in a given plot imply different combinations of flexion and rotation cause different sensitivities for the preoperative measurements; hence, there is likely to be an interaction.

Figure 4: Representative 2D projections of the proximal femur flexion on y-axis and external rotation on the x-axis. Measurements on the images are the mean values for all shapes. Red arrows represent an apparent decrease from the neutral evaluation; green denotes the opposite while an equals sign denotes minimal difference from neutral. Note: highly flexed femora appear to be abducted in 2D due to the distal end moving closer to the source and the X-ray path being diverted laterally see figure 6.

Figure 5: Neutral orientation (0° flexion and 0° external rotation) distributions of FO, NSA and GT-FHC for both female (n = 50) and male groups (n = 50).

Figure 6: X-ray path through an identical point on the same femur in a neutral and flexed orientation. Highly flexed femora appear to be abducted in 2D due to the distal end moving closer to the source and the X-ray path being diverted laterally.
**Electronic supplement**

Movie reporting the separate and combined influence of flexion and external rotation on Femoral Offset (FO), Neck Shaft Angle (NSA) and the distance (parallel to the femoral axis) from greater trochanter to femoral head centre (GT-FHC).
*** = p<0.001, ** = p<0.01, * = p<0.05