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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 center (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 center 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.

1. Introduction

Reconstruction of femoral geometry, in particular femoral head center (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

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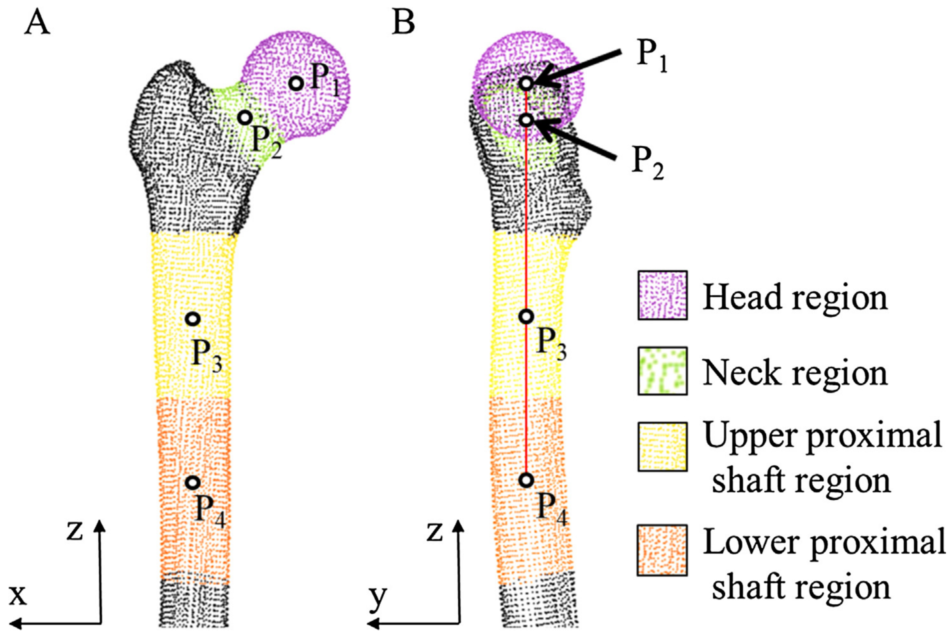

Fig. 1. Views from the anteroposterior (A) and mediolateral (B) direction of the head, neck, and proximal shaft regions identified on the mean shape. The mediolateral view (B) shows the neutral alignment of the femur in both rotation and flexion axes.

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 center (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 (Fig. 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; Fig. 1). The FHC (P1) was determined using a sphere-fit function on points in the head region (Fig. 1). Femora were neutralized by aligning the plane formed by P1, P3 and P4 with the X-Z plane (coronal plane) of the coordinate frame (Fig. 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 center of the femoral head and from the source to the detector plane (1.2 m in all cases). Since the projected points retained the same order for all shapes, regions could be identified