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Highlights

- Little focus on femoral head height in total hip arthroplasty
- Relative reliability of radiographic landmark references unknown
- This simulation study modelled different femoral orientations
- Error shown to be common and greater trochanter more sensitive to rotation

Influence of Preoperative Femoral Orientation on Radiographic Measures of Femoral Head Height in Total Hip Replacement

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28 **Influence of Preoperative Femoral Orientation on Radiographic Measures of Femoral Head**
29 **Height in Total Hip Replacement**

30 **ABSTRACT**

31 *Background*

32 In total hip arthroplasty the surgeon aims to restore the biomechanics of the joint. Femoral height has
33 the greatest influence on restoring limb length and contributes equally to the restoration of femoral
34 head centre. On X-ray, the level of femoral neck resection is most often referenced off the upper
35 border of lesser trochanter. Less frequently, femoral head centre is referenced from the tip of the
36 greater trochanter. **The error in measurement of femoral height resulting from unknown femoral**
37 **rotation is crucially important and can result in inappropriate surgical planning for implant selection**
38 **and placement. It is unknown which reference produces lower error.**

39 *Methods*

40 A sample of femoral shapes was generated using a femoral statistical shape model. These were
41 placed in a range of orientations in terms of external rotation and flexion, at intervals of 10°.
42 Simulated X-rays were then produced and the distances from the tip of either greater or lesser
43 trochanter to femoral head centre were measured.

44 *Findings*

45 Although using greater trochanter as a reference demonstrated greater errors at the extremes, both
46 techniques resulted in errors of 7-8 mm with 20° of both femoral external rotation and flexion.

47 *Interpretation*

48 Moderate degrees of femoral external rotation combined with flexion can result in unsatisfactory
49 errors when templating limb length. There should be greater focus and an agreed definition for
50 femoral height. **There is a clinical need for a method with a lower error in determining true femoral**
51 **height and the level of neck resection.**

52 **Keywords:** femoral height, preoperative planning, limb length, total hip arthroplasty

53 INTRODUCTION

54 Part of the aim of **total hip arthroplasty** (THA) is to restore hip biomechanics. On the femoral side
55 along with femoral offset, femoral height makes a critical contribution, particularly in restoring limb
56 length [1,2]. Preoperative templating for THA is typically performed on an anteroposterior (AP)
57 pelvic X-ray with the restoration of femoral head centre (FHC) being a key goal on the femoral side
58 of the joint. This has two components in the coronal plane: (i) femoral offset and (ii) femoral height.
59 In the literature *femoral offset* as a term is well-established and is consistently defined as the
60 horizontal distance from the femoral anatomical axis to FHC [3]. Femoral height on the other hand,
61 which is the major determinant of postoperative limb length and arguably the greatest source of
62 error, is not instantly recognised as a term and does not have a consistent definition. When measuring
63 the femoral contribution to limb length on X-ray, it can be defined as the vertical distance between
64 FHC and the apex of lesser trochanter (LT) or the vertical distance between FHC and the tip of the
65 greater trochanter (GT) as shown in Figure 1. Most commonly during surgery, the level of neck
66 resection is referenced from the superior limit of LT, which can be directly visualised. Alternatively,
67 some surgeons will reference FHC from the tip of GT but this bony landmark can only be accurately
68 located using a needle. Normally on a preoperative X-ray, both the apex of the LT and the tip of GT
69 are sharply defined whereas the superior border of the LT, as during surgery, does not have a sharp
70 endpoint.

71 Again, concerning preoperative templating, there is a general awareness of the potential errors in
72 femoral offset and neck shaft angle measurement on the AP X-ray in the presence of femoral
73 external rotation and flexion [4,5]. However, there is less understanding of the impact of the
74 combination of femoral external rotation and flexion on the measurement of femoral height,
75 particularly whether the reference of GT or LT is more reliable [4]. **These rotations during imaging**
76 **are common and error in measurement (the difference between true and apparent) can lead to**

77 misinterpretation of femoral anatomy and inappropriate surgical planning [5]. This in turn may affect
78 decisions on implant choice, component placement and ultimately patient outcomes. The problem
79 can be visualised in Figure 1 where the left femur shows a true AP (i.e. 0° external and 0° flexion).
80 When external rotation is combined with flexion, FHC incorrectly projects more proximally relative
81 to surrounding bony femoral anatomy.

82 Limb length discrepancy (LLD) alters postoperative biomechanics following THA and is a common
83 source of patient dissatisfaction as well as a frequent reason for litigation [2,6,7]. Specifically, limb
84 lengthening in contrast to limb shortening results in the greatest dissatisfaction and it is important to
85 understand the aetiology [8]. Acetabular or hip centre, as with FHC, is determined by the height and
86 offset. The literature indicates that postoperatively, acetabular offset and height tend to be reduced
87 [9]; therefore, cup placement per se would normally lead to a modest decrease in limb length. When
88 using a cementless cup, as was the case in 67.6% of THA surgeries in the UK National Joint Registry
89 for 2018, it is technically difficult to increase acetabular height beyond that of its premorbid state
90 [10]. This means that any significant limb lengthening following THA is almost invariably caused by
91 an error in femoral height [11]. This, in turn, is caused by making the femoral neck resection too
92 high, resulting in a proud stem and an increase in femoral height.

93 Previous research suggests that a difference of ≥ 5 mm can be perceived by 74% of controls and
94 THA patients and 12.5 mm by 100% of subjects in a cohort of 73 individuals (Female: Male – 44:29,
95 mean [SD] age – 66 [8], mean [SD] BMI – 27.9 [4.9]) [12]. A range of negative outcomes has been
96 previously associated with limb length changes after THA including pain and dislocation [11]. More
97 recently, a study of 123 participants (Female: Male – 75:48, mean [SD] age – 68.5 [11.3], mean [SD]
98 BMI – 28.6 [5.2]) found that an increase in femoral height that is insufficient to produce a
99 symptomatic LLD can still result in a poorer one year outcome [13]. It is therefore clear from the
100 literature that a much greater focus and recognition of femoral height is required both during

101 templating and surgery. This study aims to quantify the magnitude of errors of FHC height
102 measurement as determined by either GT-FHC or LT-FHC when using an X-ray that is not a true AP
103 (i.e. external rotation and flexion are simultaneously present).

104 **METHODS**

105 *Dataset of femoral shapes*

106 The dataset of femoral shapes was produced using a statistical shape model, previously described [4],
107 to facilitate automated measurement of GT-FHC and LT-FHC. Segmented femurs (30 male, M, and
108 42 female, F) from the Virtual Skeleton Database (SICAS, Swiss Institute for Computer-Assisted
109 Surgery, Switzerland) were used to build the statistical shape models in Scalismo (R0.12, Graphics
110 and Vision Research Group, University of Basel, Switzerland) [14,15]. Two models were built: one
111 using the male femoral shapes and the other using the female equivalent. The shape variation
112 described from the first 10 modes of the model equated to 96% for the males and 98% for the
113 females. A total of fifty shapes were then generated from each model (n=100; M:F = 50:50) by
114 random generation of shape parameters; these values were drawn from a normal distribution and
115 were limited to ± 3 standard deviations. Shapes generated using this method all have the same
116 number of points (approximately 19,000) with each point being in roughly the same anatomical
117 location across individuals. This key advantage allowed for measurement to be automated, without
118 which the analysis of combined rotations would not be feasible within a practical timeframe.

119 *Femoral orientation*

120 All shapes were put in a consistent neutral orientation by aligning the plane formed by three points:
121 (i) head centre, (ii) anatomical axis in the upper proximal region, and (iii) anatomical axis in the
122 lower proximal region. This was achieved in MATLAB (R2015b, The MathWorks, Inc., USA). Each
123 shape was also translated so the femoral head centre was at the origin (zero point in X, Y and Z

axes). Similar to a previous study, the shapes were then assigned an external rotation followed by flexion [4]. The range for each rotation was from 0° to 50° in 10° increments leading to a total of 36 distinct orientations being simulated.

Simulated X-rays

X-ray imaging of the femora in these orientations was then simulated in MATLAB using a previously described algorithm [16,17]. The process involved joining a source point to each point on the femur and then calculating the intersection with the X-ray detector plane (Figure 2). In line with typical clinical practice, the source-image distance (SID) was 1.2 m [5,18]. The FHC was offset from the central beam by 90 mm (the approximate average distance from the midline of the body to the FHC, reflecting the clinical practice of directing the central beam to the pubic symphysis) [9]. The 2D image was magnified by the ratio of SID to the source-object distance (SOD); since SOD is fixed at a value of 1 m, the magnification factor was 1.2 in all cases. Magnification correction was performed for all measurements taken on each 2D image. The FHC in 2D was located using the circle-fit function in MATLAB on the boundary points of the head region. To identify the tip of GT, the head and neck points were excluded, and the remaining points were sorted by their Z-coordinate; the largest value was the GT tip. The equation of the line perpendicular to the femoral shaft axis and through the GT tip was then constructed and GT-FHC was calculated. If FHC was below GT, it was assigned a negative sign and a positive sign if above. The tip of LT was identified by constructing a line at the base of LT and finding the point on the LT perpendicular and furthest away from the baseline. The distance (along the vertical axis of the image) to the FHC was then defined as LT-FHC (Figure 1).

Statistical analysis

All statistical analysis was performed in the R statistical software environment [19]. Linear mixed-effects models, as opposed to standard multivariate linear regression, were used for statistical

analysis due to multiple measurements being made on the same shapes; the *lme4* package was used for model fitting [20]. Mixed-effects models combine fixed effects, that are assumed to affect only the mean (e.g. rotation), and random effects that affect variability (e.g. due to unquantified subject-specific differences). Separate models were fitted for LT-FHC error and GT-FHC error as the dependent variables; in all cases the 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). A squared term (for both external rotation and flexion) was added as an independent variable given the relationship was non-linear. The models allowed for a different intercept for each participant. The *MuMIn* package [21] facilitated calculation of R^2 values for both fixed effects (marginal R^2 , hereafter denoted by R_m^2) and the overall model including random effects (conditional R^2 , hereafter denoted by R_c^2). The R-squared value estimates the variance explained by the fixed effects (i.e. rotations and sex) part of the model (in the case of R_m^2) and the variance explained by the model as a whole (i.e. including fixed effects of rotations and sex as well as the random intercept) in the case of R_c^2 . Table 1 shows the coefficients of the fixed effects part of the model which represent the expected change in measurement error for changes in external rotation, flexion, and sex. These coefficients were used to produce predictions from the model and associated confidence intervals (Figure 3).

RESULTS

A large proportion of the variance in the GT-FHC measurement was explained by sex, external rotation, flexion and subject-specific differences (Table 1; $R_c^2 = 0.97$). The R_c^2 for the LT-FHC was lower at 0.85 (Table 1). Interaction terms had a significant effect ($p < 0.001$) on both measures showing that combined rotations had a large influence on the preoperative planning measures. This suggests the effect of each rotation on measurement cannot be assessed in isolation, e.g. the effect of external rotation on GT-FHC is dependent on the degree of flexion.

171 The error in GT-FHC was relatively unaffected by uniaxial rotation, i.e. where either flexion or
172 external rotation was kept neutral (Figure 3). In contrast, combined rotations led to significant errors
173 which were more severe at higher rotations. The trend for LT-FHC was more non-linear; error
174 increased up to 20° but higher rotations led to less severe errors than with GT-FHC (Figure 3).

175 Figure 4 shows the measurements on the mean shape at different levels of rotation. The mean value
176 for GT-FHC at neutral orientation was -12.2 mm (i.e. FHC was 12.2 mm *below* the tip of GT)
177 whereas the value at 50° external and 50° flexion was 17.0 mm (i.e. FHC was 17.0 mm *above* the tip
178 of GT); this represents an error of 29.2 mm at the extreme of the range of combined rotations. At
179 neutral orientation, the LT-FHC measure was 51.9 mm. The largest error for LT-FHC was 10.0 mm,
180 significantly lower than GT-FHC (Figure 3). However, if we look just at the more likely
181 combination of 20° of external rotation and flexion, the error for GT-FHC was 8.1 mm and the error
182 for LT-FHC was 7.4 mm (Figure 5). The difference between the two techniques is now small and
183 these degrees of femoral external rotation and flexion would be expected to be more common than
184 the more extreme values. The error in GT-FHC was increased in male femoral shapes by 1.55 mm
185 (95% CI: 1.10–2.00) independent of rotation.

186 **DISCUSSION**

187 This study aimed to determine the magnitude of errors of femoral height measurement as determined
188 by either GT-FHC or LT-FHC when using an X-ray that is not a true AP (i.e. external rotation and
189 flexion occurring together). A simulation study was performed and an important link between
190 combined femoral external rotation and flexion, and error in FHC height measurement was
191 demonstrated. The GT-FHC measure was shown to have 29.2 mm of error with a combination of
192 external rotation and flexion of 50° each whereas, under the same conditions, the largest error for
193 LT-FHC was much less at 10 mm. However as can be appreciated from a clinical perspective, the
194 appearance of external rotation and flexion of 50° as illustrated in the top right image of Figure 4 is

195 rarely seen whereas the appearance of external rotation and flexion of 20° as illustrated in Figure 5 is
196 certainly not infrequent on a preoperative X-ray. In fact, in this projection, FHC is at the level of the
197 GT which many surgeons consider to be normal. Certainly, in this study, FHC was never above the
198 tip of GT when a femur was in neutral orientation. In the scenario of external rotation and flexion of
199 20° both techniques have errors of between 7 and 8 mm, which, when combined with magnification
200 and intraoperative measurement errors, could approach 10 mm [22].

201 The placement of components in THA has a strong influence on the biomechanics of the restored
202 joint. Unfavourable reconstruction of hip geometry can lead to changes in muscle moment arms,
203 which change the amount of force production required for movement [23]. Limb length
204 discrepancies in THA patients are associated with reduced gait velocity and contact forces
205 postoperatively [2]. The vast majority of individuals can detect a difference in limb length of 10 mm
206 and therefore during surgery the surgeon should aim to restore limb length with discrepancies less
207 than 10 mm [12]. However, the evidence from this study suggests that this level of accuracy can be
208 challenging with many preoperative X-rays. Thus, there is a need for both a greater focus and
209 understanding of femoral height during THA. At present the term *femoral height* does not have an
210 agreed definition. At times there can be new bone formation around the tip of the GT, whereas loss
211 of definition around the LT is very uncommon. We, therefore, propose that femoral height would be
212 best defined as: *the distance from FHC to the apex of the LT along the vertical axis of the image.*

213 In conclusion, moderate degrees of femoral external rotation, when combined with flexion can result
214 in unsatisfactory errors when templating limb length. **Use of lesser trochanter as a reference (as**
215 **opposed to greater trochanter) may lead to lower error in measurement of femoral height, particularly**
216 **at high external rotation and flexion. At low/moderate combined external rotation and flexion, both**
217 **methods had an error of 7–8mm.** There is a need to either improve the quality of preoperative X-
218 rays, use other modalities such as CT, or find better ways of determining the level of neck resection

219 intraoperatively to restore FHC. There is also a need for more emphasis on femoral height and an
220 agreed definition.

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223 **Conflict of interest**

224 David Beverland has received funding from DePuy Synthes and Zimmer Biomet but not directly for
225 this work.

226 **Ethical approval**

227 Anonymised imaging data was provided under a creative commons license (CC BY-NC-SA) by the
228 Swiss Medical Image Repository. Data acquisition was fully anonymised and controlled by a
229 governmental data protection agency (Datenschutzbeauftragter Stadt Bremen, Bremen, Germany).

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231 Author contributions: 1) Study concept and design – JOC, JH, DEB, ND, AL; 2) Acquisition of data
232 – JOC, AL; 3) Analysis and interpretation of data – JOC, JH, DEB, ND, AL; 4) Drafting of the
233 manuscript – JOC, JH, DEB, ND, AL; 5) Critical revision of the manuscript for important
234 intellectual content – JOC, JH, DEB, ND, AL

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294

295 **FIGURE AND TABLES**

296 Table 1: Results of statistical analyses showing unstandardised coefficients (B) of the fixed parts of the mixed effects models, 95% confidence intervals
 297 (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.
 298 The R-squared value estimates the variance explained by the fixed effects (i.e. rotations and sex) part of the model (in the case of R_m^2) and the variance
 299 explained by the model as a whole (i.e. including fixed effects of rotations and sex as well as the random intercept) in the case of R_c^2 . The coefficients of
 300 the fixed effects part of the model represent the expected change in measurement error for changes in external rotation, flexion, and sex. The Flexion² and
 301 External² terms model the non-linear changes. The Flexion: External parameter defines the dependence of measurement error on the interaction between
 302 the two rotational axes.

	<i>LT-FHC error</i>			<i>GT-FHC error</i>		
	<i>B</i>	<i>CI</i>	<i>p</i>	<i>B</i>	<i>CI</i>	<i>p</i>
Intercept	-0.64	-1.10 – -0.18	0.007	-1.33	-1.68 – -0.98	<0.001
Flexion	0.37	0.36 – 0.38	<0.001	0.22	0.21 – 0.23	<0.001
Flexion ²	-0.007	-0.0070 – -0.0066	<0.001	-0.0038	-0.0040 – -0.0037	<0.001
External	0.15	0.14 – 0.16	<0.001	0.10	0.09 – 0.11	<0.001
External ²	-0.0027	-0.0029 – -0.0025	<0.001	-0.0014	-0.0016 – -0.0012	<0.001
Flexion: External	0.0031	0.0029 – 0.0033	<0.001	0.0111	0.0110 – 0.0113	<0.001
Sex (male)	0.48	-0.12 – 1.09	0.12	1.55	1.10 – 2.00	<0.001
R_m^2	0.69			0.96		
R_c^2	0.85			0.97		

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304

305

Figure 1. Measurement of femoral head height using greater trochanter (GT-FHC) and lesser trochanter (LT-FHC) as a reference. The femur is in neutral orientation on the left while the femur on the right is in an externally rotated and flexed orientation. The GT-FHC measurement is parallel to femoral axis while the LT-FHC is along the vertical axis of the image.

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307

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Figure 2. Simulated X-ray imaging setup.

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310

311 Figure 3: Interaction plots showing the relationship between flexion and the predicted value (95%
 312 confidence interval) of the fitted models for GT-FHC and LT-FHC at different levels of external
 313 rotation.

314

315 Figure 4: Representative 2D projections of the proximal femur varying in both external rotation and
 316 flexion.

317

Figure 5. Projection of femur in 20° external rotation and 20° flexion. The error values for this orientation are similar on average at 8.1 mm for GT-FHC and 7.4 mm for LT-FHC.

Conflict of interest statement

David Beverland has received funding from Depuy Synthes and Zimmer Biomet but not directly for this study. Other authors report no conflicts of interest regarding this work.