ORIGINAL ARTICLE

Relation between lower extremity alignment and proximal femur anatomy. Parameters during total hip arthroplasty

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KEYWORDS
Total hip arthroplasty; Femoral offset; Lower extremity alignment; Adult; Biomechanics

Summary

Background: Lower extremity alignment correlates with native femoral offset. Eventual impact of the change in femoral offset induced by total hip arthroplasty (THA) on lower extremity alignment has not been documented.

Hypothesis: THA significantly changes lower extremity alignment, and the change correlates with the change in femoral offset.

Materials and methods: We conducted a prospective study of 200 patients with primary hip osteoarthritis or avascular femoral head necrosis who underwent cementless THA. Pre-operative computed-tomography templating was performed and the femoral component was then custom-manufactured to replicate the native femoral anatomy. Mean age was 58 years (range, 28–83 years). Before and at least two years after THA, two observers who were not involved in the surgical procedures used standing antero-posterior long-leg radiographs to determine the mechanical axis of the lower-limb (hip-knee-ankle [HKA] angle), femoral offset, neck-shaft angle (NSA), and lower-limb length discrepancy (LLLD).

Results: Mean values pre-operatively and at last follow-up were as follows: HKA angle, 179.2° ± 3.9° (range, 170.5° to 190.5°) and 177.7° ± 3.5° (range, 173° to 187°); LLLD, −0.7 mm (range, −30 mm to +25 mm) and +5.1 mm (range, −7 mm to +21 mm); NSA, 134° ± 7.5° (range, 100° to 124°) and 135° ± 4.2° (range, 124° to 146°); and femoral offset, 42 ± 7.8 mm (range, 24 mm to 68 mm) and 49 ± 7.5 mm (range, 33 mm to 70 mm). Although THA significantly altered lower-limb alignment, univariate and multivariate analyses showed no significant association between the change in HKA angle and the change in femoral offset.

Discussion: Lower-limb alignment was significantly affected by THA, although the HKA angle changes were small. The small impact of THA on HKA angle values may be ascribable to efforts aimed at replicating the native femoral offset during arthroplasty, as well as to the limited sample size and to potential measurement errors related to the small size of the changes. Our results suggest that, provided careful attention is directed to replicating the native femoral...
Introduction

Many factors have been incriminated in the pathogenesis of femoro-tibial osteoarthritis including body weight, gender, heavy manual labour, and lower-limb geometry [1–8]. Studies have documented the impact of knee alignment on the development of femoro-tibial osteoarthritis [9,10]. A number of anthropometric and anatomical parameters characterising the hip joint may also affect the risk of knee osteoarthritis [11]. Femoral offset (FO) is the distance between the centre of rotation of the femoral head (CRF) and the anatomical axis of the femoral shaft [12]. As emphasised by Steinberg and Harris [13], FO plays a key role in hip biomechanics by governing the balance between body weight and hip abductor strength [14–20]. Kerboul investigated the impact of abnormal hip biomechanical parameters in patients with hip ankylosis or high-grade hip dysplasia [21]. Weidow et al. [11] reported a significant association between the development of femoro-tibial osteoarthritis and the native FO value. Nevertheless, no such association has been documented after FO modification induced by total hip arthroplasty (THA).

Our working hypothesis was that THA-induced changes in hip biomechanics significantly altered lower-limb alignment. The primary objective of our study was to assess the reliability and reproducibility of our radiographic analysis technique. Our secondary objectives were to evaluate the impact of THA-induced changes in hip biomechanics on lower-limb alignment and to look for correlations in subgroups defined based on pre-operative lower-limb alignment (varus, neutral or valgus).

Material and methods

Patients

A prospective single-centre study was conducted between 1993 and 2007 in patients with primary hip osteoarthritis or avascular femoral head necrosis who were scheduled for sequential bilateral THA by two senior surgeons (JNA and JMA), with an interval of at least two years between the two procedures. Exclusion criteria were as follows: age younger than 18 years or older than 85 years, history of surgery or trauma affecting one or both hips, and underlying disease other than primary osteonecrosis or avascular femoral head necrosis (dysplasia, fracture, inflammatory disease, or tumour) affecting one or both hips.

We included 200 patients, 112 (56%) women and 88 (44%) men with a mean age of 58 ± 11 years (range, 28–83 years). Mean body mass index was 26.24 ± 4.8 kg/m² (range, 15–40 kg/m²). The first THA was performed on the right side in 57% of cases. The mean time interval between the two THA procedures was 33.6 months.

All patients underwent two THA procedures according to the same protocol: patient in the supine position; modified Watson-Jones approach, use of a femoral component that was custom-made based on pre-operative computed-tomography (CT) templating, with the goal of restoring native FO, and implanted without cement (SymposiaSM, Yverdon, Suisse) and a cementless cup (SymposiaSM, Yverdon, Suisse).

Measurement methods

FO was measured pre-operatively then at last follow-up, i.e., at the time of the radiographic work-up performed to prepare for the second THA procedure. All measurements were performed at the same centre, using the same method, on a standard standing hip radiograph obtained by a senior radiologist who placed the lower-limb as near as possible to 15° of internal rotation pre-operatively and post-operatively. Radiograph magnification was corrected using a standard scaling technique (1-cm metal bead).

Lower-limb alignment was assessed pre-operatively then at least two years post-operatively on standing antero-posterior long-leg radiographs performed at a single radiology centre using the same protocol, with the lower-limbs in controlled rotation. Measurements on each anonymised radiograph were performed manually by two observers working independently of each other, at an interval of one month. The second observer was not informed of the results obtained by the first observer. The following lower-limb biomechanical parameters were measured manually on each radiograph (Fig. 1 and 2): FO [12], neck-shaft angle (NSA) between the longitudinal axis of the native or prosthetic neck and the anatomical axis of the femoral shaft [13], and HKA angle between the mechanical axis of the femur and the mechanical axis of the tibia [22]. The radiographs were also used to assess the pre-operative severity of the hip osteoarthritis, presence of osteoarthritis of the femoro-tibial and patello-femoral knee compartments, and lower-limb length discrepancy (LLLD) before and after THA.

Statistical methods

Demographic characteristics of the study patients and radiographic parameters were described as mean ± SD. The required sample size was estimated before the study assuming a mean pre-operative FO of 42.90 ± 5.43 mm and a mean pre- to post-operative change in FO (ΔFO) of 1.88 ± 4.71 mm [23]. To enable the detection of a 2-mm ΔFO on long-leg radiographs with α = 0.05 and 1–β = 0.95, 50 patients per group were required for the subgroup analysis. Inter- and intra-observer repeatabilities of radiographic measurements were assessed using the Bland and Altman method [24] and measurement reproducibility using intra-class correlation coefficients (ICCs). A univariate analysis of the pre- to post-operative changes (Δ) in radiographic parameters.
was performed using Students t test and linear regression. Analyses were also performed in the following subgroups:

- three lower-limb alignment subgroups, namely:
  - varus defined as a pre-operative HKA angle inferior to 178°,
  - neutral alignment defined as 178° inferior to HKA angle inferior to 182°, and,
  - valgus defined as HKA angle superior to 182° and;
- three ΔFO subgroups, namely:
  - decrease by more than 3 mm,
  - change smaller than 3 mm in either direction and,
  - increase by more than 3 mm.

A multivariate analysis of associations among these parameters was performed. The statistical tests were done at the public health and medical informatics department of the Sainte-Marguerite Hospital (Marseille, France) using SPSS software (version 12; SPSS Inc., Chicago, IL, USA).

Results

We included 200 hips in 200 patients meeting our inclusion and exclusion criteria. The ICC used to assess measurement reproducibility was 0.809 for the pre-operative measurements and 0.796 for the post-operative measurements. These values are considered to indicate good reproducibility. The repeatability analysis based on the Bland and Altman method [24] showed a mean pre-operative HKA angle difference between the two observers of 0.53° with a 95% confidence interval (95%CI) of −3.95° to 5°. The difference between the two evaluations was not affected by the HKA angle value. For the mean post-operative HKA angle, the difference was −0.96 with a 95%CI of −5.47° to 3.54°. These data are reported in Table 1 and illustrated in Fig. 3, which show diagrams of the reproducibility analyses of the pre- and post-operative HKA angles.

The univariate analysis showed the following THA-induced changes (Table 2): FO, from 42.03 ± 7.85 mm (range; 24 to 68 mm) to 49.90 ± 7.55 mm (range, 33 to 70 mm) (P < 0.001); HKA angle, from 179.2 ± 3.96°

Table 1 Reproducibility and repeatability of the radiographic measurements. Intra-observer reproducibility was assessed using the intra-class correlation coefficient and repeatability using the Bland and Altman method (plot of the measurement value difference between the two observers against the mean of the two values in each patient).

<table>
<thead>
<tr>
<th>Radiographic measurement</th>
<th>Inter-observer repeatability (ICC)</th>
<th>Bland and Altman method (mean error between observers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-operative HKA angle</td>
<td>0.809</td>
<td>0.53°</td>
</tr>
<tr>
<td>Post-operative HKA angle</td>
<td>0.796</td>
<td>95%CI, −3.95° to 5°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>−0.96°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>95%CI, −5.47° to 3.54°</td>
</tr>
</tbody>
</table>

ICC: intra-class correlation coefficient; 95%CI: 95% confidence interval.
Table 2: Results of the univariate analysis of changes in studied radiographic parameters. The data are mean ± SD (range) in mm and degrees. Values of $P < 0.05$ were considered significant.

<table>
<thead>
<tr>
<th>Radiographic parameters</th>
<th>Pre-operatively</th>
<th>At last follow-up</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Femoral offset</td>
<td>42.03 ± 7.85 mm (24 to 68 mm)</td>
<td>49.90 ± 7.55 mm (33 to 70 mm)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>HKA angle</td>
<td>179.20 ± 3.09° (170.5° to 190.5°)</td>
<td>177.75 ± 2.93° (172 to 187°)</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>NSA</td>
<td>134.34 ± 7.51° (100° to 124°)</td>
<td>135.43 ± 4.62° (124° to 146°)</td>
<td>0.143</td>
</tr>
<tr>
<td>LLLD</td>
<td>−0.74 ± 5.72 mm (−30 to +25 mm)</td>
<td>+5.1 ± 5.94 mm (−7 to +21 mm)</td>
<td>&lt; 0.001</td>
</tr>
</tbody>
</table>


The changes in the other radiographic parameters were smaller than the predefined significance level. The pre-operative assessment of the ipsilateral knee showed no osteoarthritis in 131 (65%) patients, whereas 65 (33%) patients were Ahlbäck grade 1, one (0.5%) patient was Ahlbäck grade 2, two (1%) patients were Ahlbäck grade 3, and one (0.5%) patient had severe Ahlbäck grade 4 knee osteoarthritis. These data were unchanged at last follow-up two years later; the patient with severe knee osteoarthritis underwent medial unicompartmental knee arthroplasty one year after the ipsilateral THA procedure (which was not followed by documented symptom exacerbation).

No correlations were identified by the analyses of biomechanical parameters. Univariate and multivariate analyses were performed to determine whether the changes in lower-limb alignment were associated with $\Delta$FO or with the changes in the other parameters. By univariate analysis, no significant association was found between $\Delta$FO and $\Delta$HKA ($P = 0.110$, Fig. 4). By linear regression analysis of correlations, $\Delta$FO was not significantly associated with $\Delta$HKA ($R^2 = 0.04$, Fig. 4).

The subgroup analysis showed the following pre-operative distribution of lower-limb alignment categories: 120 (60%) patients had neutral alignment with a mean HKA angle of 179.8° ± 3.9°, 50 patients had varus malalignment with a mean HKA angle of 175.9° ± 1.5°, and 30 patients had valgus malalignment with a mean HKA angle of 183.9° ± 2.9. Table 3 reports the results of the univariate subgroup analysis. The multivariate subgroup analysis showed no clear correlation between $\Delta$FO (adjusted on the pre-operative value) and the HKA angle measured two years after THA. Table 4 reports the results of the univariate analysis of subgroups defined based on $\Delta$FO. $\Delta$HKA showed no significant differences across the three $\Delta$FO subgroups (greater than 3-mm decrease in FO, $\Delta$FO between −3 mm and + 3 mm, and greater than 3 mm increase in FO).

Discussion

Re-establishing the original FO improves THA stability, decreases polyethylene wear, and enhances gluteus medius efficiency [14,16,19,25–27]. Native-hip FO has been shown to affect lower-limb alignment [18]. In contrast, to our knowledge no previous studies assessed the potential impact of FO changes after THA on lower-limb alignment. Here, our working hypothesis was that THA-induced changes in hip biomechanical parameters influenced lower-limb alignment and, more specifically, that this influence was ascribable in
Figure 4 Analysis of the correlation between the THA-induced change in femoral offset and the THA-induced change in hip-knee-ankle (HKA) angle. X-axis: Δfemoral offset, Y-axis: ΔHKA angle.

Table 3 Univariate analysis of the difference between pre- and post-operative biomechanical parameter values in three subgroups defined based on pre-operative lower-limb alignment (varus, hip-knee-ankle angle inferior to 178°; neutral alignment, 178° inferior to hip-knee-ankle angle inferior to 182°; valgus, hip-knee-ankle angle, superior to 182°). The data are mean ± SD in mm or degrees. Values of P < 0.05 were considered significant.

<table>
<thead>
<tr>
<th>Pre-op. HKA</th>
<th>Post-op. HKA</th>
<th>Pre-op. offset, mm</th>
<th>Post-op. offset, mm</th>
<th>Pre-op. LLLD, mm</th>
<th>Post-op. LLLD, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Varus n=120</td>
<td>Value 177</td>
<td>44.41</td>
<td>50.97</td>
<td>−1.08</td>
<td>6.26</td>
</tr>
<tr>
<td></td>
<td>± 1.98</td>
<td>± 7.59</td>
<td>± 8.24</td>
<td>± 4.57</td>
<td>± 5.74</td>
</tr>
<tr>
<td>P value</td>
<td>0.053</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Normal n=50</td>
<td>Value 179.2</td>
<td>42</td>
<td>49</td>
<td>−0.7</td>
<td>6.30</td>
</tr>
<tr>
<td></td>
<td>± 2.95</td>
<td>± 7.85</td>
<td>± 7.55</td>
<td>± 5.7</td>
<td>± 5.94</td>
</tr>
<tr>
<td>P value</td>
<td>0.4</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valgus n=30</td>
<td>Value 182.7</td>
<td>39</td>
<td>48.33</td>
<td>0.83</td>
<td>6.44</td>
</tr>
<tr>
<td></td>
<td>± 2.18</td>
<td>± 6.77</td>
<td>± 6.50</td>
<td>± 7.50</td>
<td>± 7.25</td>
</tr>
<tr>
<td>P value</td>
<td>0.2</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pre-op.: pre-operative; post-op.: post-operative; HKA: hip-knee-ankle angle; LLLD: lower-limb length discrepancy.

Table 4 Univariate analysis of the difference between pre- and post-operative biomechanical parameter values in three subgroups defined based on the change in femoral offset induced by total hip arthroplasty: greater than 3-mm decrease; change no greater than 3 mm in either direction; and greater than 3-mm increase. The data are mean ± SD in mm or degrees (range). Values of P < 0.05 were considered significant.

<table>
<thead>
<tr>
<th>ΔOffset, mm</th>
<th>ΔHKA</th>
<th>Δ &gt; 3°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease by more than 3 mm Mean change, 5.5 ± 1.1 mm n=14</td>
<td>0.25 ± 1.45 (0 to 3)</td>
<td>1 patient</td>
</tr>
<tr>
<td>Change ±3 mm Mean change, 0.76 ± 2 mm n=73</td>
<td>0.2 ± 1.9 (0 to 5)</td>
<td>7 patients</td>
</tr>
<tr>
<td>Increase by more than 3 mm Mean change, 11 ± 4.7 mm n=113</td>
<td>0.32 ± 2.27 (0 to 5.7)</td>
<td>13 patients</td>
</tr>
<tr>
<td>P value</td>
<td>0.8</td>
<td></td>
</tr>
</tbody>
</table>

Δ: change from pre-operative to post-operative; HKA: hip-knee-ankle angle.

part to ΔFO. Two independent observers performed measurements on pre- and post-THA long-leg radiographs of 200 patients with primary hip osteoarthritis or avascular necrosis. The measurement values were then used to assess associations between FO and the HKA angle reflecting lower-limb alignment. THA induced significant changes in both FO and the HKA angle. However, the statistical analysis failed to identify any significant correlations between ΔFO and ΔHKA. An analysis of subgroups defined based on the pre-operative HKA angle value (neutral alignment, valgus, or varus) also showed no significant association between ΔFO and ΔHKA. Similarly, an analysis of subgroups defined based on ΔFO identified no significant differences in ΔHKA.

Several limitations of our study indicate a need for caution when interpreting our findings:

- first, ΔFO was not significantly correlated with the HKA angle, although both parameters were significantly modified by THA. A number of factors may contribute to explain this finding. The sample size was modest, although no patients were lost to follow-up. A sample size estimation was performed before the study with β < 10% and α = 5%. Nevertheless, a larger sample might have produced significant differences for some of the comparisons. Similarly, subgroup sizes were limited. Factors such as pre-operative LLLD and ipsilateral knee osteoarthritis may have confounded the ΔHKA results [9]. To minimize this source of bias, factors significantly associated with lower-limb alignment by univariate analysis were entered into a multivariate analysis;

- the main evaluation criteria used in our study were radiographic parameters, which may have resulted in measurement bias. The method described by Steinberg and Harris for measuring FO on standard radiographs has been challenged by authors who advocate the use of more accurate techniques [23]. Pasquier et al. [23] reported that both pre- and post-operative radiographic FO measurement led to under-estimation by 3.28 ± 4.11 mm (range, 0 to 12.5 mm), i.e., to 8% of measurement error, compared to 3D CT measurement. Radiograph magnification varies across protocols and machines, and the incidences used vary across radiology centres. However, we used a single machine at a single radiology centre, and we applied a standard technique to correct for magnification. FO measurement has been shown to depend directly on patient position during radiograph acquisition [28], with lower-limb rotation producing the largest differences, of up to 25 mm for the same hip. Similarly, excessive anteverision or torsion of the native femur may affect FO measurement;

- when evaluating the impact of hip biomechanical parameter changes induced by THA in patients with hip osteoarthritis, the presence and time-course of osteoarthritis of the ipsilateral knee should be investigated. However, given the short follow-up duration in our study, we did not obtain detailed information on knee osteoarthritis;

- the use of radiographs instead of CT scans may have resulted in measurement bias. However, the measurements performed by the two senior radiologists were validated before our analysis;

- finally, bias may have occurred during the statistical analysis, as challenges arise when building a statistical model to evaluate correlations between two variables geometrically related to each other (here, FO and HKA angle). We elected to start by assessing the differences between pre- and post-operative values then to assess correlations between ΔFO and ΔHKA. Such use of multiple statistical models can induce statistical bias and alter a normally significant difference. Despite these biases, to our knowledge, ours is the only prospective study of correlations between ΔFO and ΔHKA conducted in a large sample of patients.

In our study, THA significantly altered hip biomechanics by increasing mean FO and significantly decreasing the HKA angle. The combination of these two changes may explain the significant increase in lower-limb length. This effect was not evaluated or predicted during pre-operative planning but has been reported even with the use of a limb-length and FO optimisation device during THA [29]. Importantly, FO and the HKA angle are necessarily related to each other. Therefore, the absence in our study of a deleterious “clinical” effect of FO restoration on lower-limb alignment requires confirmation by longer-term studies including assessments of osteoarthritis severity in the ipsilateral knee. One possibility, however, is that THA-induced FO changes within the range seen in our study may have no effect on lower-limb alignment. Re-establishing an “ideal” FO can improve the lever arm of the hip abductors [14,15] and decrease the rate of polyethylene wear without altering the biomechanics of the ipsilateral knee. Thus, in our patients without major pre-operative deformities (osteoarthritis or avascular necrosis), FO restoration using a custom-made implant resulted in a mean 7-mm increase in FO without mean HKA angle changes in excess of 3°.

Femoro-tibial osteoarthritis is a multifactorial disease [1–7] related in part to the biomechanical characteristics of the knee [8]. The HKA angle is a validated tool for assessing lower-limb alignment [22], whose alterations are associated with the development of medial or lateral femoro-tibial osteoarthritis [9]. Many factors can affect the HKA angle [10], including native FO [11]. To obtain a comprehensive analysis of associations linking native and prosthetic FO to the HKA angle change after THA, we divided our population into three subgroups depending on whether the pre-operative HKA angle value indicated valgus, normal alignment, or varus. No significant differences in ΔHKA were found across these three subgroups. Thus, lower-limb alignment is independent from ΔFO even in groups with outlying values.

FO measurement and the impact of FO changes have generated controversy since the work done by Bourne and Rorabeck [15]. The challenge consists in determining the optimal FO value in patients with hip abnormalities. Using the contralateral hip as a point of reference for pre-operative planning has limited reliability [30]. Statistical 2D geometric construction based on a pelvic dimension as described by Pierchon et al. may be more accurate [31]. However, 3D CT templating is highly accurate
in ensuring restoration of hip biomechanical parameters [23—25]. Although current knowledge of the relations between FO and hip biomechanics remains limited, many studies indicate that FO plays a key role in lower-limb function and aging, although the underlying mechanisms remain unclear [11,16,19]. Our study provides new information about the potential effects of THA-induced FO changes on lower-limb alignment at least two years after THA. Restoring or even increasing the FO value during THA does not seem to modify the HKA angle and would therefore not be expected to affect the risk of ipsilateral knee osteoarthritis.

Our study demonstrates that THA significantly modifies radiographic FO. Our objective was to evaluate the impact of FO modification on lower-limb alignment. Our statistical analysis showed no correlation between these two variables. Studies in larger samples involving FO measurement on CT images are needed to elucidate the relations among proximal femur biomechanical parameters and the potential impact of these parameters on lower-limb function.

Disclosure of interest
Sébastien Paratte is a consultant for Zimmer, Graftys, and Adler and receives royalties from Euros. Xavier Flecher is a consultant for Zimmer and receives royalties from Euros. J.-N. Argenson is a consultant for Zimmer and Convatech and receives funding from Stryker and Adler and royalties from Zimmer and Symbios. M. Ollivier and L. Lecoz declare that they have no conflicts of interest concerning this article.

References

