**HIP**

Variation in functional pelvic tilt in patients undergoing total hip arthroplasty


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*Aims*

The pelvis rotates in the sagittal plane during daily activities. These rotations have a direct effect on the functional orientation of the acetabulum. The aim of this study was to quantify changes in pelvic tilt between different functional positions.

*Patients and Methods*

Pre-operatively, pelvic tilt was measured in 1517 patients undergoing total hip arthroplasty (THA) in three functional positions – supine, standing and flexed seated (the moment when patients initiate rising from a seated position). Supine pelvic tilt was measured from CT scans, standing and flexed seated pelvic tilts were measured from standardised lateral radiographs. Anterior pelvic tilt was assigned a positive value.

*Results*

The mean pelvic tilt was $4.2^\circ$ (-20.5° to 24.5°), $-1.3^\circ$ (-30.2° to 27.9°) and $0.6^\circ$ (-42.0° to 41.3°) in the three positions, respectively. The mean sagittal pelvic rotation from supine to standing was $-5.5^\circ$ (-21.8° to 8.4°), from supine to flexed seated was $-3.7^\circ$ (-48.3° to 38.6°) and from standing to flexed seated was $1.8^\circ$ (-51.8° to 39.5°). In 259 patients (17%), the extent of sagittal pelvic rotation could lead to functional malorientation of the acetabular component. Factoring in an intra-operative delivery error of ± 5° extends this risk to 51% of patients.

*Conclusion*

Planning and measurement of the intended position of the acetabular component in the supine position may fail to predict clinically significant changes in its orientation during functional activities, as a consequence of individual pelvic kinematics. Optimal orientation is patient-specific and requires an evaluation of functional pelvic tilt pre-operatively.

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Various guidelines have been proposed for the orientation of the acetabular component in total hip arthroplasty (THA).1–4 The most commonly cited guidelines date back to 1978.4,5 So-called ‘safe-zones’ aim to identify ranges for inclination and anteversion within which the risk of dislocation, edge-loading, prosthetic wear and impingement will be minimised. However, various authors have challenged the relevance of these zones and highlighted the lack of consensus between various guidelines.6–11 In a series of more than 9000 THAs, Abdel et al10 showed that more than half of the dislocations occurred with acetabular components which were placed within the safe-zone.

The guidelines for inclination and anteversion have been determined through analysis of failed or retrieved components in comparison with a control group.1–4 The analyses of the angles were performed using either radiographs or CT, with the patient supine, lying static on a radiographic table. However, dislocation, edge-loading and impingement more commonly occur during activities when the position of the pelvis, and thus the acetabular component, could be significantly different to that seen with static, non-functional imaging. The variation in sagittal pelvic tilt between supine and more functional positions was first described in 2003 and was shown to be highly patient-specific.9–11 DiGioia et al11 showed an unpredictable arc of sagittal pelvic movement as large as 70° in their series of 84 patients. Lazennec et al10 found similar ranges, and introduced the notion that the lumbar spine has an influence on the functional tilt of the pelvis in the supine, standing and seated positions. More recently, several authors have repeated these studies and confirmed the findings.12–14 Evidently, the pelvis is a mobile structure, with the degree of movement specific to each individual.
Any kinematic variation in sagittal pelvic tilt will have a substantial effect on the functional anteversion and inclination of the acetabulum. As the pelvis rotates posteriorly, with the iliac spines moving posteriorly relative to the pubic tubercles, the functional anteversion of the acetabular components will increase (Fig. 1). This rotation will protect against dislocation and edge-loading in flexion of the hip, but can lead to anterior instability and wear in extension. By contrast, anterior rotation of the pelvis, where the iliac spines rotate anteriorly relative to the pubic tubercles, reduces the functional anteversion of the acetabulum, protecting against dislocation and edge-loading in extension of the hip, but not in flexion (Fig. 1). Therefore, it seems more relevant to investigate the orientation of the acetabular component not when the patient is supine, but in functional flexion and extension when the problems associated with malorientation of the component are likely to occur.

All previously published studies of seated pelvic tilt involved patients who were positioned upright, in a natural seated posture. However, during activities commonly associated with posterior dislocation and edge-loading, such as rising from a chair, bending or tying up shoe laces, the hip is flexed further, with the patient’s body leaning forward in order to reach their feet, or to enable a biomechanically-efficient sit-to-stand. Consequently, a more representative measure of the patient’s functional pelvic tilt in flexion will be obtained if measurements are performed in a flexed seated posture, and not the standard relaxed seated posture previously reported (Fig. 2).

The aim of this observational study was to measure the sagittal pelvic tilt in patients awaiting THA in the supine, standing and flexed seated positions.

Patients and Methods
Between January 2014 and December 2015, a consecutive series of 1517 patients underwent pre-operative CT scans and lateral functional radiographs as part of routine planning for THA. The mean age was 63 (22 to 90); 798 (53%) were men. The imaging was performed according to the OPS Dynamic Hip Analysis protocol (Optimized Ortho, Sydney, Australia). The low dose CT protocol is based on the work of Huppertz et al and results in a mean dose of 2.8 to 4.0 mSv per scan. The OPS planning software is a commercially-available medical device. All images were analysed by qualified engineers (JP and BM), and independently inspected by a second engineer.

The sagittal orientation of the pelvis was defined by the pelvic tilt, which is the angle between the coronal plane and the anterior pelvic plane (APP). The APP is a pelvic reference plane defined by the left and right anterior superior iliac spines (ASIs) and the midpoint of the pubic tubercles. Pelvic tilt was measured in the supine, standing and flexed seated positions (Fig. 2). Supine pelvic tilt was measured in Solidworks 2013 (Dassault Systèmes, Vélizy-Villacoublay, France) as the angle between the coronal plane and the APP in a 3D reconstruction from CT scans. Standing and flexed seated pelvic tilt was measured from lateral functional radiographs as the angle between the coronal plane and the
APP (Fig. 2). In the standing position, the x-ray beam was centred on L5 to enable the entire lumbar spine and pelvis to be in the field of view. In the flexed seated position, an adjustable stool was used to ensure that the femurs remained parallel to the floor. All imaging was controlled using a standardised protocol (Optimized Ortho, Sydney, Australia).

An anterior pelvic tilt, where the ASISs were anterior to the pubic tubercles, was assigned a positive value. Conversely, a posterior pelvic tilt, in which they were located posterior relative to the pubic tubercles, was assigned a negative value.

Each individual’s sagittal pelvic rotation, described as the change in pelvic tilt between positions, was calculated. An anterior sagittal pelvic rotation, in which the ASISs rotate anteriorly relative to the pubic tubercles, was assigned a positive value. A posterior sagittal pelvic rotation, in which they rotate posteriorly relative to the pubic tubercles, was assigned a negative value. An absolute pelvic rotation was also calculated, representing the magnitude of rotation, without regard to the direction. A pelvic rotation of ≥13° between positions was considered extreme, as it would result in a ≥10° change in the functional anteversion of the acetabular component.15

Each patient’s lumbar lordotic angle (LLA) was also measured in the standing and flexed seated positions from the lateral radiographs. LLA was defined as the angle between the superior endplates of L1 and S1 (Fig. 2). Lumbar flexion was defined as the difference between the LLA when standing and when flexed seated.

Statistical analysis. Standing pelvic tilt and positional changes were compared with standing LLA and lumbar flexion respectively, using the Pearson correlation coefficient. The slope of the line of best fit was used to predict the effect of LLA and lumbar flexion on functional pelvic tilt. Data were analysed using Matlab 2015 (MathWorks, Natick, Massachusetts).

The retrospective analysis was approved by Bellberry Human Research Ethics Committee, study number 2012-03-710.

Results
The mean values for the supine pelvic tilt, the LLA and lumbar flexion in the three functional positions are shown in Table I and the mean absolute changes in pelvic tilt between these positions in Table II.

The pelvis rotated posteriorly by ≥13° in 92 patients (6%) between the supine and standing positions, putting them at risk of excessive functional anteversion in extension; and it rotated anteriorly in 167 patients (11%) by ≥13° between the supine to flexed seated positions, reducing the acetabular component anteversion by ≥10° in flexion putting them at risk of posterior instability or posterior edge-loading (Fig. 3b). Factoring in an intra-operative error of placement of the component of ±5° extends this risk to 772 patients (51%). Of the 259 patients (17%) with extreme pelvic movement, the pelvis rotated by ≥13° in 11 (1%) during both the supine-to-standing rotation and the supine-to-flexed seated rotation.

The Pearson correlation coefficient between LLA and standing pelvic tilt was 0.37. The relationship between lumbar flexion and sagittal pelvic rotation was weak, with Pearson correlation coefficients of 0.28 and -0.34 for the changes from the supine-to-standing, and supine-to-seated positions, respectively.

Discussion
There is a lack of consensus regarding the ideal orientation of the acetabular component when undertaking THA. This is the largest observational study to have reported pelvic tilt in a series of patients who are undergoing THA, and emphasises the significant individual variation between functional positions of the pelvis. The mean supine and standing pelvic tilts of 4.2° and -1.3° are similar to other reports.9,11,13,14,22 However, it is the considerable patient-specific range of >60° that is significant (Fig. 3a). For
example, one patient might have a 30° posterior pelvic tilt when standing and another could have a 30° anterior pelvic tilt in exactly the same standing position. Thus two individuals could have a difference of > 40° in anteverision of the acetabular component if the recommended guidelines of Lewinnek et al.4 are followed.

The mean pelvic tilt in the flexed seated position was 0.6°. This differs considerably from previous reports because of the difference in the seated position in this study. Previous authors have reported a mean seated pelvic tilt in the range of -25° to -36°, however all patients were seated in a relaxed posture, upright in a chair.9,11,13,22 In this series, all patients were asked to lean forward, flexing the body as if about to rise (Fig. 2). We believe that this represents a more appropriate position to investigate functional flexion. With the body potentially driving the pelvis into a more anteriorly tilted position, the acetabular component can become less anteverted and this represents a position at which posterior dislocation and edge-loading is more likely to occur. Interestingly, and again more relevant than the mean value, the range of > 70° is comparable with previous studies, regardless of the different seated position.

Pelvic tilt in all of the functional positions which we studied showed variations from the supine position. The interpatient variation in all positions was considerable, highlighting the importance of individual pre-operative assessment. The mean changes in position were modest, the range of > 70° is comparable with previous studies, regardless of the different seated position.

Table I. Mean values and ranges for pelvic tilt, lumbar lordotic angle and lumbar flexion in the three functional positions

<table>
<thead>
<tr>
<th>Position</th>
<th>Supine</th>
<th>Standing</th>
<th>Flexed seated</th>
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<tbody>
<tr>
<td>Mean pelvic tilt (*) (range)</td>
<td>4.2° (-20.5° to 24.5°)</td>
<td>-1.3° (-30.2° to 279°)</td>
<td>0.6° (-42.0° to 41.3°)</td>
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<tr>
<td>Mean lumbar lordotic angle (*) (range)</td>
<td>573° (-10.7° to 94.5°)</td>
<td>11.7° (-25.2° to 60.2°)</td>
<td>46.2° (0.0° to 79.7°)</td>
</tr>
<tr>
<td>Mean lumbar flexion (*) (range)</td>
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Table II. Mean changes in pelvic tilt between functional positions

<table>
<thead>
<tr>
<th>Positional change</th>
<th>Supine-to-standing</th>
<th>Supine-to-seated</th>
<th>Standing-to-seated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean pelvic rotation (*) (range)</td>
<td>-5.5° (-21.8° to 8.4°)</td>
<td>-3.7° (-48.3° to 38.6°)</td>
<td>1.8° (+51.8° to 39.5°)</td>
</tr>
<tr>
<td>Mean absolute pelvic rotation (*) (range)</td>
<td>6.0° (0.0° to 21.8°)</td>
<td>10.7° (0.0° to 48.3°)</td>
<td>11.1° (0.0° to 51.8°)</td>
</tr>
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In our study, the pelvis rotated posteriorly by ≥ 13° in 92 patients (6%) moving between the supine and standing positions, increasing anteverision of the acetabular component by ≥ 10° in extension. These patients are at risk of anterior instability and anterior edge-loading. Conversely, the pelvis rotated anteriorly by ≥ 13° in 167 patients (11%), decreasing anteverision of the component by ≥ 10° when moving between the supine and flexed seated positions, putting them at risk of posterior edge-loading and instability in flexion. These data suggest that about 17% of patients are at risk of functional malorientation of the acetabular component due to extreme sagittal pelvic rotation (Fig. 4a). These observations are based on the assumption that an acetabular orientation of precisely 40°/20° has been achieved intra-operatively. In reality, even the most sophisticated navigation systems have a reported error of ± 5°.23,24 If this error is incorporated into the calculations, the number of patients at risk of functional acetabular malorientation increases to 51% (Fig 4b). With the precision of freehand implantation being within 10° of the intended target in only 50% of cases, the value of identifying a patient-specific target is evident. Interestingly, there was a small group of patients (1%) who were at risk of functional malorientation in both flexion and extension. Perhaps this subset of patients would benefit from a bearing that provides additional stability such as a dual mobility bearing. Regardless, pre-operative knowledge of an individual patient’s
range and direction of pelvic rotation will help to optimise planning the position of the components.\textsuperscript{25}

An individual’s sagittal pelvic position is determined by the relationship between the hip and the spine.\textsuperscript{16,26} Consequently, progression of osteoarthritis in either the hip or the spine will affect the functional pelvic tilt. Flexion deformities of the hip might induce an anterior pelvic tilt, as might acetabular dysplasia as a natural mechanism for increasing lateral cover. Furthermore, lumbar lordosis can decrease with age as the spine stiffens, and the pelvis will compensate by tilting posteriorly in an attempt to maintain sagittal balance.\textsuperscript{27} Previous studies have concluded that it is the flexibility of the lumbar spine that defines an individual’s sagittal pelvic movement, suggesting that a patient with a flexible spine will have less pelvic movement than one with a stiff spine.\textsuperscript{13,14,16,28,29} It has therefore been suggested that the target angles for the orientation of the acetabular component can be made by analysis of spinal disease alone.\textsuperscript{28} In this series we also observed many patients whose extreme pelvic motion was attributable to spinal disease or fusion, however it was undoubtedly not the only cause for such changes. The Pearson correlation coefficient between the LLA and standing pelvic tilt was low, 0.37. Furthermore, the relationship between lumbar flexion and sagittal pelvic rotation was also weak, with Pearson correlation coefficients of 0.28 and -0.34 for supine-to-standing and supine-to-seated rotations, respectively. This analysis would suggest that many patients with extreme pelvic motion do not necessarily have spinal pathology. Consequently, we caution against limiting pre-operative functional analysis to only patients with spinal pathology.

We measured pelvic tilt from pre-operative imaging of patients requiring THA. As the hips were osteoarthritic, the functional pelvic tilt might change post-operatively. Several authors have examined changes of pelvic tilt in both the standing and seated positions. Several authors have examined changes of pelvic tilt in both the standing and seated positions.
are no significant differences between the pre- and post-operative values. In the standing position, Taki et al and Kanawade et al reported a mean posterior change of between 2° and 4° post-operatively. Ishida et al went one step further and identified that the amount of change is a function of the patient’s pre-operative pelvic tilt. Patients with a large anterior pelvic tilt pre-operatively had much larger posterior changes post-operatively. Although pelvic tilt might change significantly in some patients, pre-operative pelvic tilt is still the best predictor of the position of the pelvis after the operation. For this reason, we routinely measure functional pelvic tilt pre-operatively. Furthermore, any planning algorithm for optimal alignment of the acetabular component should incorporate published evidence to predict individual changes in functional pelvic tilt as a consequence of THA.

This study has limitations. First, the reasons for dislocation and edge-loading are multifactorial, and although functional malorientation of the acetabular component is a contributing factor, there are other causes to consider. Bearing contact mechanics, soft-tissue impingement, anteversion of the femoral component, leg length inequality, medial and anterior offset, soft-tissue laxity, surgical approach and the size of the femoral head can all contribute to dislocation and edge-loading. Given the patient-specific ranges in sagittal pelvic motion, it is evident that functional orientation of the acetabular component can play a significant role in the mechanisms of failure. Secondly, only movement of the pelvis in the sagittal plane was measured. Any coronal or axial rotation of the pelvis in functional positions would also affect acetabular orientation. It is likely however, that such changes would be small.
in comparison with sagittal pelvic rotation and significant variations would be apparent on standard imaging. We did not measure the pelvic incidence or the spinopelvic tilt. These parameters are likely to show a stronger correlation to functional changes in sagittal pelvic positioning and are the subject of on-going work. We did not perform a reliability and repeatability study for the technique of measurement of pelvic tilt. However, all measurements were performed by a qualified engineer as part of the planning process for THA, and each landmark was verified by a second engineer. Finally, there was a difference in imaging modalities between measurements taken when supine (CT) and when standing and flexed seated (radiograph). The data for the supine measurements have a narrower distribution, which is likely to be a function of less variation in the supine position, but also may be a result of the precision of the CT methodology over plain films.

In conclusion, the position of the pelvis in the sagittal plane may vary significantly between functional positions. The extent of change is specific to each individual. As a result of these changes, the angles of orientation of the acetabular component during dislocation and edge-loading will be different from those measured from standard CT and radiographs. Therefore, previously defined ‘safe zones’ for the orientation of the component might not be appropriate for all patients as they do not account for the kinematic behaviour of the pelvis. Pre-operative, functional evaluation is recommended, as planning and measurement of the placement of the acetabular component in the supine position alone may lead to suboptimal orientation in more functionally-relevant positions.

Take home message: An evaluation of functional pelvic tilt is required to determine a patient’s optimal component orientation.

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References


