Functional orientation of the acetabular component in ceramic-on-ceramic total hip arthroplasty and its relevance to squeaking

Aims
Long-term clinical outcomes for ceramic-on-ceramic (CoC) bearings are encouraging. However, there is a risk of squeaking. Guidelines for the orientation of the acetabular component are defined from static imaging, but the position of the pelvis and thus the acetabular component during activities associated with edge-loading are likely to be very different from those measured when the patient is supine. We assessed the functional orientation of the acetabular component.

Patients and Methods
A total of 18 patients with reproducible squeaking in their CoC hips during deep flexion were investigated with a control group of 36 non-squeaking CoC hips. The two groups were matched for the type of implant, the orientation of the acetabular component when supine, the size of the femoral head, ligament laxity, maximum hip flexion and body mass index.

Results
The mean functional anteversion of the acetabular component at the point when patients initiated rising from a seated position was significantly less in the squeaking group than in the control group, 8.1° (-10.5° to 36.0°) and 21.1° (-1.9° to 38.4°) respectively (p = 0.002).

Conclusion
The functional orientation of the acetabular component during activities associated with posterior edge-loading are different from those measured when supine due to patient-specific pelvic kinematics. Individuals with a large anterior pelvic tilt during deep flexion might be more susceptible to posterior edge-loading and squeaking as a consequence of a significant decrease in the functional anteversion of the acetabular component.
defined from measurements on static radiographs with the patient positioned supine.8,15 However, the position of the pelvis, and thus the acetabular component, during activities associated with edge-loading are likely to be very different from those measured when the patient is supine.16-18 This is due to patient-specific differences in the position of the pelvis during the course of an activity.

The aim of this study was to investigate the functional orientation of the acetabular component in patients with squeaking CoC bearings, with the hypothesis that seemingly well-orientated components on routine radiographs can be functionally malorientated due to an individual's sagittal pelvic kinematics.

Patients and Methods
All 26 patients with squeaking from a previous study, investigating the incidence of squeaking in large diameter Delta Motion CoC bearings (DePuy Orthopaedics, Warsaw, Indiana), were contacted.7 A total of 18 patients consented to be included in further analysis. Reproducible squeaking was confirmed by means of the Melbourne Orthopaedic Noise Assessment grading system.7 The diameter of the femoral head was 40 mm, 44 mm or 48 mm. All patients had reproducible squeaking during deep flexion. No patient had squeaking in extension. The femoral components included 12 Trilock stems (DePuy Orthopaedics), five Finsbury Type-C stems (Finsbury Orthopaedics, Surrey, United Kingdom) and one SL Plus stem (Smith & Nephew, Memphis, Tennessee). A control group of 36 patients with Delta Motion bearings without squeaking were recruited from the silent cohort of the original study.7 They were matched to the squeaking group for the type of implant, the diameter of the femoral head, supine acetabular component inclination and anteversion, Beighton scores, and maximum flexion of the hip and body mass index, (see Table I). The pelvic tilt and sacral slope were measured on lateral radiographs in two functional positions – standing and seated – with the body flexed as if about to rise (Figs 1 and 2). The angles in these two positions were used to define the functional position of the pelvis at the limits of flexion and extension of the hip, respectively. The orientation of the acetabular component and pelvic tilt when supine were

Table I. Matched characteristics of the study groups. Body mass index, maximum hip flexion, Beighton scores, supine acetabular component inclination and anteversion are presented as mean values (ranges)

<table>
<thead>
<tr>
<th></th>
<th>Squeaking group (n = 18)</th>
<th>Silent control group (n = 36)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass index (kg/m²)</td>
<td>27.0 (19.2 to 32.8)</td>
<td>27.2 (19.6 to 33.0)</td>
<td>0.922</td>
</tr>
<tr>
<td>Maximum hip flexion (°)</td>
<td>109 (90 to 130)</td>
<td>109 (90 to 140)</td>
<td>0.938</td>
</tr>
<tr>
<td>Supine acetabular component inclination (°)</td>
<td>35.1 (22.7 to 44.0)</td>
<td>37.5 (20.0 to 52.0)</td>
<td>0.191</td>
</tr>
<tr>
<td>Supine acetabular component anteversion (°)</td>
<td>16.0 (6.6 to 24.8)</td>
<td>19.5 (7.8 to 32.1)</td>
<td>0.071</td>
</tr>
<tr>
<td>Beighton score</td>
<td>1.7 (0.0 to 7.0)</td>
<td>1.4 (0.0 to 5.0)</td>
<td>0.632</td>
</tr>
<tr>
<td>Head sizes, n (%)</td>
<td>40 mm 8 (44)</td>
<td>14 (39)</td>
<td>0.245</td>
</tr>
<tr>
<td></td>
<td>44 mm 7 (39)</td>
<td>13 (36)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>48 mm 3 (17)</td>
<td>9 (25)</td>
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</tr>
</tbody>
</table>

Fig. 1
Photograph showing a patient in the flexed seated position. The torso is brought forward over the feet to allow standing.

Fig. 2a
Examples of the two lateral radiographs used to define the functional position of the pelvis in the sagittal plane; a) the standing position – the pelvic tilt is -3°; b) the flexed seated position – the pelvic tilt is now 33°, a change of 36°.

Fig. 2b

Table I. Matched characteristics of the study groups. Body mass index, maximum hip flexion, Beighton scores, supine acetabular component inclination and anteversion are presented as mean values (ranges)
assessed on low-dose CT scans using 3D registration of the virtual Delta Motion implant geometry in CAD (Simpleware v5.1, Exeter, United Kingdom) by three observers (JP, HF and BM). Murray’s radiographic definitions were used for all component orientation measurements. Both anterior superior iliac spines and the pubic symphysis were also identified in order to define the anterior pelvic plane (APP). All observers performed each registration three times, at weekly intervals. The intra- and inter-observer correlation coefficients of agreement were calculated for the mean results of each observer. Measurements of anteverision and inclination were made independently using the first assessment of each observer. Inter-observer correlation coefficients were also calculated to assess reliability, with the least consistent observer reported.

Knowing the pelvic tilt in the supine, standing and flexed seated positions from the radiographs and the orientation of the acetabular component with reference to the APP from the CT scans, the functional orientation of the acetabular component was calculated as described by Lembeck et al. Anteverision of the femoral component was also measured from the CT scans with reference to the posterior femoral condyles.

The study had ethical approval; the trial number was 157.

**Statistical analysis.** The data were assessed for normality using the Shapiro-Wilk test. As the data could not be shown to deviate from normality, a two-tailed student’s t-test was used to investigate the statistical significance between the two groups. Statistical significance was set at p = 0.05. Data were analysed using Matlab 2015 (Math-Works, Natick, Massachusetts).

### Results

The intra-class correlation coefficients for inter- and intra-observer reliability were 0.989 and 0.984 for anteverision, and 0.995 and 0.993 for inclination, respectively, indicating extremely high reliability. In vitro studies have shown that a complex chain of events is required to generate a reproducible squeak in a CoC bearing. The process begins with the formation of a wear stripe on the prosthetic head, generated during edge-loading. Once the magnitude of the reaction force reaches a critical limit and is directed through the stripe, reproducible squeaking is observed.

### Discussion

The mean pelvic tilt in the flexed seated position was statistically higher in the squeaking group than in the control group (p = 0.039). The mean functional anteverision of the acetabular component in the flexed seated position and when standing was significantly less in the squeaking group than in the control group (p = 0.002 and p = 0.025, respectively). There was no significant difference in the inclination of the components between the two groups in any of the three functional positions (Table II).

The mean pelvic tilt in the flexed seated position was statistically higher in the squeaking group than in the control group (p = 0.039) and the mean change in pelvic tilt from standing to the flexed seated position was also significantly higher in this group (p = 0.022) (Table III). The other changes in pelvic tilt are also shown in Table III.

The mean anteversion of the femoral stem was not significantly different in the two groups (squeaking, 12.3°; -3.3° to 24.7° and control, 14.3°; -0.9° to 33.8°, respectively, p = 0.490).

### Table II. The orientation of the acetabular component in three positions presented as mean values (ranges)

<table>
<thead>
<tr>
<th></th>
<th>Squeaking group</th>
<th>Silent control group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supine acetabular component orientation measured from anteroposterior radiographs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination</td>
<td>35.1° (22.7° to 44.4°)</td>
<td>37.5° (20.0° to 52.0°)</td>
<td>0.191</td>
</tr>
<tr>
<td>Anteverision</td>
<td>16.0° (6.6 to 24.8°)</td>
<td>19.5° (7.8 to 32.1°)</td>
<td>0.071</td>
</tr>
<tr>
<td>Supine acetabular component orientation measured from CT</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination</td>
<td>33.6° (23.8° to 43.9°)</td>
<td>35.9° (20.4° to 49.2°)</td>
<td>0.199</td>
</tr>
<tr>
<td>Anteverision</td>
<td>16.5° (5.0° to 31.5°)</td>
<td>21.3° (8.4° to 31.8°)</td>
<td>0.032</td>
</tr>
<tr>
<td>Acetabular component orientation from CT and adjusted to stand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination</td>
<td>34.6° (26.7° to 44.7°)</td>
<td>37.6° (21.8° to 51.8°)</td>
<td>0.081</td>
</tr>
<tr>
<td>Anteverision</td>
<td>20.3° (2.5° to 35.2°)</td>
<td>26.2° (10.4° to 41.6°)</td>
<td>0.025</td>
</tr>
<tr>
<td>Acetabular component orientation from CT and adjusted to flexed seated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inclination</td>
<td>33.4° (22.8° to 49.0°)</td>
<td>36.2° (21.3° to 48.3°)</td>
<td>0.149</td>
</tr>
<tr>
<td>Anteverision</td>
<td>8.1° (-10.4° to 36.0°)</td>
<td>21.1° (-1.9 to 38.4°)</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Values in bold indicate statistical significance.

### Table III. Pelvic tilt in different functional positions presented as mean values (ranges)

<table>
<thead>
<tr>
<th></th>
<th>Squeaking group</th>
<th>Silent control group</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supine pelvic tilt</td>
<td>-2.6° (-8.8° to 10.4°)</td>
<td>4.9° (-5.5° to 16.0°)</td>
<td>0.134</td>
</tr>
<tr>
<td>Standing pelvic tilt</td>
<td>-1.8° (-18.0° to 9.4°)</td>
<td>-1.2° (-14.1° to 12.9°)</td>
<td>0.784</td>
</tr>
<tr>
<td>Flexed seated pelvic tilt</td>
<td>12.6° (-13.5° to 30.3°)</td>
<td>5.1° (-9.8° to 26.4°)</td>
<td>0.039</td>
</tr>
<tr>
<td>Pelvic tilt change from supine to stand</td>
<td>-4.4° (-13.9° to 4.8°)</td>
<td>-6.2° (-21.1° to 4.6°)</td>
<td>0.213</td>
</tr>
<tr>
<td>Pelvic tilt change from stand to flexed seated</td>
<td>14.4° (-9.2° to 31.0°)</td>
<td>6.3° (-18.3° to 27.8°)</td>
<td>0.022</td>
</tr>
</tbody>
</table>

Values in bold indicate statistical significance.
Squeaking can be heard, even in well lubricated conditions. Theoretically therefore, if the initial edge-loading event can be avoided, squeaking should not occur.

Edge-loading is not only dependent on the 3D movement of the femur, but also on the force vector across the hip, as well as the pelvic kinematics of the patient. All of these factors influence the likelihood of edge-loading during an activity of daily living by changing the location of the bearing contact area in relation to the edge of the liner.

Sagittal pelvic kinematics are highly variable between individuals and between different functional activities. As individual pelvic rotations have a substantial effect on the functional orientation of the acetabular component, the likelihood of edge-loading as the patient rises from a seated position or during gait is specific to each individual. Furthermore, the orientation of the acetabular component as the patient initiates rising from a seated position or during gait, could be very different from that measured when the patient is supine. For example, a patient may have an apparently well-orientated component when supine, yet their sagittal arc of pelvic movement may result in the component being functionally malorientated on rising from the seated position, potentially leading to posterior edge-loading (Fig. 3). Conversely, the component may be excessively anteverted or inclined during gait, due to patient-specific changes in pelvic kinematics from the supine to standing positions, causing anterosuperior edge-loading.

The functional anteversion in the squeaking group in the flexed seated position was significantly less than in the control group (Fig. 4). This was primarily due to the increased anterior tilt of the pelvis in the seated position in this group. The reasons for variation in the sagittal pelvic kinematics of patients are likely to include a combination of factors, including, but not limited to age, gender, spinal pathology,
sagittal balance, body shape, pathology in the contralateral hip and soft-tissue stiffness. These variables and their effect on the sagittal kinematics of the hip are currently a subject of further investigation.

Large changes in the functional position of the pelvis in the sagittal plane between the standing and sitting positions have been described, with a sagittal arc of pelvic movement as large as 70°. However, the seated position considered in these studies was a relaxed posture with the patient’s back resting on a straight-backed chair. This position is unlikely to be the functional posture at the time of rising from a chair, when squeaking is commonly observed. The patient’s centre of gravity must move anteriorly over the feet to allow standing. Large anterior pelvic tilts on rising from the seated position have been seen by other authors using “motion capture”. The functional position of the pelvis in the sagittal plane is different in the relaxed seated position and the position when rising from a chair.

Although the two groups were matched for anteversion of the acetabular component when supine, there was an unforeseeable difference when standing. Firstly, the matching of the orientations of the component when supine was performed using EBRA-derived data from the original study. Due to the large head CoC bearings, there is a margin of error in defining the ellipse of the posterior aspect of the acetabular component using this software. This accounted for the variation in the measurement of anteversion when supine between CT and AP radiographs. This discrepancy was confounded in the standing position by a larger posterior change from the supine to standing positions in the control group than in the squeaking group. Consequently, the acetabular components in the control group had higher functional angles of anteversion when standing. This highlights the patient-specificity of pelvic kinematic changes not only from seated to standing but also from supine to standing. These changes could not be anticipated from standard supine AP radiographs.

Large heads were introduced with the intention of providing more “natural biomechanics”, increased stability and improved mechanics. In order to facilitate large head articulations in relatively small acetabular components, the centre of rotation is usually projected several millimetres out from the face of the acetabular component in order to maintain sufficient thickness of material at the...
apex of the component, to increase the range of movement before impingement and to stiffen the construct to resist deformation during impaction.\textsuperscript{32,33} However, offsetting the centre of rotation reduces the functional articulating arc of the bearing and increases the likelihood of edge-loading.\textsuperscript{10,31,32} The Delta Motion bearings in this study all were $\geq 40$ mm in size, with projected centres of rotations of 2 mm to 3 mm from the face of the acetabular component (Fig. 5). This results in a low “Cup Articular Arc Angle” (CAAA) of 158° for all sizes. Interestingly however, this is not the case for sizes of head of $\leq 36$ mm. The centre of rotation is maintained level with the face of the component, resulting in an increased CAAA of 169°. This challenges the theory of improved contact mechanics and reduced edge-loading with larger heads. Furthermore, offsetting the centre of the femoral head has been shown to reduce the prosthetic jump distance, theoretically reducing stability.\textsuperscript{37} Therefore, the size of the head must be considered in conjunction with the design of the acetabular component when investigating stability, contact mechanics and the prevalence of edge-loading.

This study has limitations. First, only sagittal plane kinematics were considered. Any coronal or axial rotation of the pelvis during standing or in the flexed seated position would also affect the functional orientation of the acetabular component. However, the changes in pelvic obliquity and roll are likely to be negligible in the two functional positions which were investigated. Similarly, coronal and axial rotations of the femur during flexion could alter the prevalence of posterior edge-loading.\textsuperscript{35} The largest arc of movement of the pelvis is in the sagittal plane and will have the greatest effect on the functional anteversion of the acetabular component. Furthermore, measurements were made in both groups of patients with the same set of assumptions regarding the axial and coronal kinematics. Consequently, any differences induced by considering sagittal rotations only, would have been similar in both groups. Secondly, although we have shown that the functional orientation of the acetabular component alone is an important factor relating to squeaking, the size and location of the contact patch of the bearing and its relationship to the true edge of the liner has been shown to be a better predictor of edge-loading in hard-on-hard bearings.\textsuperscript{36,37} The distance between the area of contact on the bearing surface and the true rim of the liner can be described by the Contact Patch to Rim Distance (CPRD) (Fig. 6).\textsuperscript{36} This distance provides an objective measure of edge-loading by considering the 3D orientation of the acetabular component, along with implant-related variables such as the subtended arc angle, the size of the head and bearing clearance. Furthermore, the CPRD can account for patient-specific variations in the magnitude and direction of the reaction force, in combination with individual kinematics. Future work should incorporate patient-specific hip loading in combination with the functional orientation of the acetabular component to provide further insight into optimal positioning.

In conclusion, the orientation of the acetabular component during activities associated with edge-loading are likely to be very different from those measured when supine. Patients with large anterior pelvic tilts during deep flexion, might be more susceptible to posterior edge-loading and squeaking in CoC bearings as a consequence of a decrease in the functional anteversion of the acetabular component. If these patients can be identified pre-operatively, the orientation of the component and choice of bearing can be modified to accommodate these individual patterns of movement.
Take home message:
Functional orientation of the acetabular component is more clinically relevant than supine static assessments.

Author contributions:
J. W. Pierrepont: Study design, Data collection, Data analysis, Writing the paper.
H. Feyen: Data collection.
B. P. Miles: Study design, Data analysis.
D. A. Young: Performed surgeries.
J. V. Baré: Performed surgeries.
A. J. Shimmin: Study design, Performed surgeries.

No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.

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References