A kinematic comparison of fixed- and mobile-bearing knee replacements

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Mobile-bearing posterior-stabilised knee replacements have been developed as an alternative to the standard fixed- and mobile-bearing designs. However, little is known about the in vivo kinematics of this new group of implants. We investigated 31 patients who had undergone a total knee replacement with a similar prosthetic design but with three different options: fixed-bearing posterior cruciate ligament-retaining, fixed-bearing posterior-stabilised and mobile-bearing posterior-stabilised. To do this we used a three-dimensional to two-dimensional model registration technique. Both the fixed- and mobile-bearing posterior-stabilised configurations used the same femoral component. We found that fixed-bearing posterior stabilised and mobile-bearing posterior-stabilised knee replacements demonstrated similar kinematic patterns, with consistent femoral roll-back during flexion. Mobile-bearing posterior-stabilised knee replacements demonstrated greater and more natural internal rotation of the tibia during flexion than fixed-bearing posterior-stabilised designs. Such rotation occurred at the interface between the insert and tibial tray for mobile-bearing posterior-stabilised designs. However, for fixed-bearing posterior-stabilised designs, rotation occurred at the proximal surface of the bearing. Posterior cruciate ligament-retaining knee replacements demonstrated paradoxical sliding forward of the femur.

We conclude that mobile-bearing posterior-stabilised knee replacements reproduce internal rotation of the tibia more closely during flexion than fixed-bearing posterior-stabilised designs. Furthermore, mobile-bearing posterior-stabilised knee replacements demonstrate a unidirectional movement which occurs at the upper and lower sides of the mobile insert. The femur moves in an anteroposterior direction on the upper surface of the insert, whereas the movement at the lower surface is pure rotation. Such unidirectional movement may lead to less wear when compared with the multidirectional movement seen in fixed-bearing posterior-stabilised knee replacements, and should be associated with more evenly applied cam-post stresses.

Recent studies have improved the understanding of the kinematic behaviour of the modern total knee replacement. It is now clear that the majority of posterior cruciate ligament (PCL)-retaining knee replacements demonstrate aberrant kinematics, with forward slide of the femoral component, whereas posterior-stabilised knee replacements (PCL-sacrificing) usually demonstrate more consistent but symmetrical posterior translation of the femoral condyles during flexion.

Mobile-bearing knee replacements may theoretically mimic the asymmetrical posterior translation of the femoral condyles which mainly occurs on the lateral side of the natural knee.

It has also become clear that classic mobile-bearing PCL-retaining knee replacements demonstrate the same aberrant kinematics as fixed-bearing PCL-retaining designs. In an attempt to improve this, mobile-bearing posterior-stabilised knee replacements have been introduced on the basis that the cam-post system might induce femoral roll-back during flexion in the same way as for fixed-bearing posterior-stabilised designs. Rotational mobility of the bearing surface could also allow a better reproduction of tibial internal rotation during flexion.

However, there is little or no information to substantiate this. Although some cadaver simulation studies have been published, very few in vivo studies exist where fixed and mobile posterior-stabilised versions of an identical design have been compared.

We have, therefore, analysed the in vivo kinematic patterns of three bearing options.
(fixed-bearing posterior-stabilised, mobile-bearing posterior-stabilised, fixed-bearing PCL-retaining) for the same design of knee replacement (Performance, Biomet-Spain, Valencia, Spain). Our aim was to investigate whether mobile-bearing posterior-stabilised knee replacements would demonstrate more favourable kinematics when compared with fixed-bearing posterior-stabilised and fixed-bearing PCL-retaining designs.

Patients and Methods
We analysed 31 patients with well-functioning total knee replacements (Performance; Biomet) using a three-dimensional (3-D) to two-dimensional (2-D) model registration technique implant superimposed during four basic movements. All patients had been operated on by the same surgeon (HPD), using the same knee replacement system but using three different configurations; fixed PCL-retaining, fixed posterior-stabilised and mobile posterior-stabilised. The Performance (Biomet) design allows the use of two different femoral components; one for the PCL-retaining configuration and the other for the fixed or mobile posterior-stabilised configurations. Both the PCL-retaining and posterior-stabilised femoral components, and their corresponding bearings, have the same sagittal radius, but differ in the coronal plane. The posterior-stabilised coronal plane condylar radius is smaller, resulting in a more rounded femoral component, while the mobile posterior-stabilised bearing is more concave in both the sagittal and coronal planes.

The distribution of the three different configurations of tibial bearing was investigated. These configurations were: fixed-bearing PCL-retaining (11 patients), fixed-bearing posterior-stabilised (10), and mobile-bearing posterior-stabilised (10). For the fixed-bearing PCL-retaining knee replacements, a posterior-lipped insert was used. Fixed- and mobile-bearing posterior-stabilised knee replacements had identical cam-post mechanisms. Comparing equal sizes of component in the femur and tibia, the contact point between a posterior-stabilised femoral component and insert theoretically occurs at 30° of flexion in the fixed and 40° in the mobile configuration. This is the result of the interactive effect of both the anteroposterior position of the post and the design of the bearing in the sagittal plane. Both PCL-retaining and posterior-stabilised fixed-bearings are secured to the tibial tray through an anterior slot, a peripheral rim and a central locking screw, whereas a posterior-stabilised mobile insert can freely rotate around a central peg on a polished tibial tray. The underside of the tray, and the tibial stem, are identical in both the fixed and mobile designs of tibial tray.

Three-dimensional positions and orientations of the femoral, tibial and mobile-bearing components were determined using shape-matching techniques. The upper row of images shows the outlines of the superimposed three-dimensional to two-dimensional model registration technique for the femur and tibial tray (left) and femur and tibial insert (right). The lower row of images show the three-dimensional to two-dimensional model registration technique projected onto the radiograph.

Three-dimensional positions and orientations of the femoral, tibial and mobile-bearing components were determined using shape-matching techniques during these activities were subsequently analysed using a 3-D to 2-D model registration technique as previously described, and allowing three-dimensional quantification of femorotibial kinematics and relative contact positions in the sagittal and coronal planes. The rotations of the mobile-bearing components were determined by using a three-dimensional model of the metal pins in the polyethylene bearing, constructed following the manufacturer’s specifications. This model was then positioned to coincide with the shape-matching solution for the tibial tray. The model was next rotated about the post on the tibial tray until the projection of the pins matched their projections on the radiological image. The precision of the internal-external rotation measurement was 0.5°. Relative movements between the femoral component and the bearing were computed using the three-dimensional positions of the two parts. No assumptions were made about the pattern of movement.

Three-dimensional positions and orientations of the femoral, tibial and mobile-bearing components were determined using shape-matching techniques (Fig. 1). Statistical analysis was performed using analysis of variance (ANOVA) with results considered significant at p < 0.05.
Results

Sagittal plane kinematics. In extension, PCL-retaining knee replacements demonstrated a tibiofemoral contact position close to the anteroposterior tibial midline, with paradoxical forward slide of the femoral component during early flexion in 83% (10 of 12 knees) of cases. With deeper flexion, particularly when > 90°, all PCL-retaining knee replacements demonstrated some posterior translation of the femoral contact point. This was a mean of 3.9 mm (-1.1 to +8.4) on the medial side and 4.8 mm (+0.4 to +9.4) on the lateral side between 90° and full flexion (Figs 2 and 3). All PCL-retaining knees exhibited posterior translation of the lateral contact point, and ten of the 12 showed posterior translation of the medial contact point. Both fixed- and mobile-bearing posterior-stabilised knee replacements demonstrated similar tibiofemoral contact positions in extension when compared with PCL-retaining designs. None of these posterior-stabilised knee replacements demonstrated paradoxical forward slide of the femur during flexion.

Between extension and maximal flexion there was a mean posterior translation of 6.4 mm (-1.5 to +10.6) on the medial side and 6.5 mm (-5.0 to +10.1) on the lateral side for the fixed-bearing posterior-stabilised knee replacements, compared with 7.2 mm (+0.6 to +16.4) medially and 7.9 mm (+3.5 to +17.2) laterally for the mobile-bearing posterior-stabilised knee replacements (p > 0.1). This was
significantly more than for PCL-retaining designs, where there was a mean posterior translation of the femoral contact point of only 0.4 mm (-6.2 to +14.6) on the medial side, and 1.4 mm (-5.1 to +8.1) on the lateral side (p < 0.001).

Flexion during maximum lunge was clearly above the degree of flexion at which cam-post engagement occurs (40° for mobile-bearing posterior-stabilised and 30° for fixed-bearing posterior-stabilised; Biomet) (Table I).

Tibiofemoral rotation. Internal rotation of the tibia during flexion was measured for each of the three designs tested (Fig. 4). The mean tibial internal rotation when kneeling fully was 5.89° (1.49° to 16.91°) for PCL-retaining designs, 2.36° (1.29° to 7.26°) for fixed-bearing posterior-stabilised knees, and 7.46° (2.05° to 15.78°) for mobile-bearing posterior-stabilised knees (p < 0.05) (Figs 5 and 6). In mobile-bearing posterior-stabilised knees, almost all rotation occurred at the distal surface between the tibial insert and the tibial tray (mean 7.63°, range 1.50° to 16.51°) whereas almost no rotation occurred at the proximal surface between femur and insert (mean 1.09°, range 2.06° to 3.23°; Figs 7 and 8).

Discussion
To our knowledge, this is the first study where the in vivo kinematic performance of both fixed- and mobile-bearing posterior-stabilised implants, with the same femoral component, have been compared with the PCL-retaining version of the same system. Our results showed that both fixed- and mobile-bearing posterior-stabilised knee replacements demonstrated similar tibiofemoral kinematic patterns with respect to femorotibial translation and axial rotation during flexion, although mobile-bearing posterior-stabilised knee replacements more closely replicated the asymmetrical posterior condylar translation of the normal knee.

Fixed-bearing posterior-stabilised knee replacements demonstrated a relatively symmetrical posterior femoral translation during flexion with a mean of 6.4 mm for the medial condyle and 6.5 mm for the lateral, which resulted in an overall tibial internal rotation of only 3.0°, which is considerably less than the 10° to 15° of tibial internal rotation which occurs in the normal knee during deep flexion. In contrast, mobile-bearing posterior-stabilised knee replacements demonstrated more asymmetrical posterior femoral translation during flexion, with a mean of 7.2 mm for the medial condyle and 7.9 mm for the lateral, resulting in a more natural tibial internal rotation of 8.0° (p < 0.05).

In our study, both fixed- and mobile-bearing posterior-stabilised knee replacements only partially restored the posterior femoral translation which occurs in the normal knee during flexion. Although no clear consensus exists on the exact data, recent work by several groups has identified that the normal knee demonstrates a negligible posterior femoral translation on the medial side, as opposed to between 15 mm and 25 mm on the lateral side, when the knee is analysed from extension to full flexion. Their findings also depend on factors such as the measurement method, muscular tone, foot position, and size of the
knee.\textsuperscript{9,13,20,21} It is clear that in our patients, posterior translation of this magnitude was not achieved, certainly not on the lateral side.

Previous work by other authors seems to confirm this observation.\textsuperscript{8,20} Most et al\textsuperscript{20} have investigated the kinematics of both the fixed- and mobile-bearing versions of the posterior-stabilised LPS knee (Zimmer Inc., Warsaw, Indiana) in a cadaver model and using a robotic testing system (Orthopaedics Biomechanics Laboratory, Harvard Medical School, Boston, Massachusetts). There was no difference between the two versions. Both fixed- and mobile-bearing posterior-stabilised knees only partially restored the posterior femoral translation and axial rotation of the normal knee. Dennis et al\textsuperscript{1} recently reported a multicentre videofluoroscopic kinematic analysis of 733 cases, including 103 mobile-bearing posterior-stabilised knees. Only limited posterior femoral translation was found, with a mean of 3.8 mm for the lateral condyle, and -0.7 mm for the medial.\textsuperscript{1} Tibial internal rotation was a mean of 3.9° from full extension to full flexion.\textsuperscript{1}

Similar values were found by Ranawat et al\textsuperscript{18} in a kinematic study which compared fixed- and mobile-bearing versions of the posterior-stabilised Sigma knee (Depuy, Warsaw, Indiana). They demonstrated greater axial rotation (4.1° vs 7.3°) and less condylar lift-off (60% vs 45%) in the fixed- vs mobile-bearing posterior-stabilised knee replacements, respectively, although the mean lateral posterior roll-back during flexion was limited for both designs (3.7 mm and 3.6 mm, respectively).

Compared with what is known from the literature, our data confirm that both fixed- and mobile-bearing posterior-stabilised knee replacements replicate axial rotation and posterior condylar translation of the natural knee during flexion, but to a lesser degree. Our patients demonstrated more posterior translation than has been reported in the literature, and greater restoration of tibial internal rotation for mobile, compared with fixed-bearing, posterior-stabilised knee replacements.

Both mobile- and fixed-bearing posterior-stabilised knee replacements demonstrated similar tibiofemoral contact positions in extension when compared with PCL-retaining knees. None of the posterior-stabilised knee replacements demonstrated paradoxical forward slide of the femur during flexion. This may be explained by the fact that we did not make any observations in early- to mid-flexion; our study was limited to a straight-leg stance and the more deeply-flexed positions.

We also analysed the pattern of tibiofemoral rotation. In the mobile-bearing posterior-stabilised knee replacements, almost all rotation occurred at the distal surface of the bearing where it articulates with the tibial baseplate. Figure 7 shows parallel lines which are different from any of the other figures and from the findings described elsewhere in the literature.\textsuperscript{1-25} Only minimal rotation appears to occur on the proximal surface of the mobile-bearing posterior-stabilised knee replacements. Theoretically, it is possible that rotation occurs at both the superior and inferior surfaces of the bearing, perhaps more likely in the unloaded than loaded state.
Compared with the fixed-bearing posterior-stabilised knee replacements, where complex translation and rotational movements occur on the proximal bearing surface, the decoupling of translation and rotation may have important theoretical benefits with regard to polyethylene wear.\textsuperscript{21-24} McEwen et al.\textsuperscript{23-25} have reported in a number of publications that ultra-high-molecular-weight polyethylene (UHMWPE) molecules become orientated in the principal direction of slide (anteroposterior), thereby producing a hardening effect which increases wear resistance. Consequently, the polyethylene softens along the axis perpendicular to the sliding movement and exhibits less wear resistance in that direction. Introducing a movement such as internal-external rotation produces a friction force in a direction which is transverse to the sliding movement and, therefore, increases the wear rate. This concept has been confirmed in knee simulator studies, comparing the \textit{in vitro} wear between the rotating platform LCS knee replacement (DePuy, Warsaw, Indiana) and the fixed-bearing Sigma knee replacement (DePuy).\textsuperscript{25} These demonstrated that the decoupling of knee movements, by allowing unidirectional rotation to occur at the insert-tibial tray articulation and unidirectional translation at the femur-insert interface, leads to reduced UHMWPE wear as a result of altered molecular orientation and decreasing cross-shear on the polyethylene.\textsuperscript{23,24} Our study demonstrates that such decoupling indeed occurs \textit{in vivo} in patients with mobile-bearing posterior-stabilised knee replacements.

The fact that mobile-bearing posterior-stabilised knee replacements demonstrate almost pure translation at the femur-insert interface has another theoretical advantage, because unidirectional translation at the proxi-

the pattern of axial rotation of a specific device is highly dependent on the surface geometry of the design used. For this reason it remains impossible to draw generalised conclusions about fixed-bearing posterior-stabilised and mobile-bearing posterior-stabilised knee replacements.

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