In vivo kinematics comparison of fixed- and mobile-bearing total knee arthroplasty during deep knee bending motion

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Abstract

Purpose The in vivo kinematics of fixed-bearing and mobile-bearing total knee prostheses remains unclear, particularly for knee flexion over 120°. The purpose of this study was to compare the in vivo kinematics of fixed-bearing and mobile-bearing posterior-stabilized prosthesis during deep knee bending with knee flexion exceeding 120° under weight-bearing conditions.

Methods In vivo kinematics was analysed for 20 patients implanted with either a fixed-bearing posterior-stabilized or mobile-bearing posterior-stabilized prosthesis. Under fluoroscopic surveillance, each patient performed weight-bearing deep knee bending. Motion between each component was analysed using a two- to three-dimensional registration technique, which uses computer-assisted design models to reproduce the spatial positions of the femoral and tibial components from single-view fluoroscopic images.

Results Patients who had fixed-bearing prostheses experienced posterior femoral rollback at a mean of 1.4 mm (SD 1.6) of the medial condyle, whereas patients who had mobile-bearing prostheses experienced 0.8 mm (SD 1.2). The posterior femoral rollback of the femoral lateral condyle in patients with a fixed-bearing prosthesis was a mean of 6.4 mm (SD 1.7) motion in the posterior direction, whereas patients who had a mobile-bearing prosthesis had 6.5 mm (SD 2.4) motion. The mean tibial internal rotation was 7.5° (SD 2.1) for fixed-bearing prosthesis and 9.2° (SD 3.2) for mobile-bearing prosthesis.

Conclusions The present results demonstrated that the fixed-bearing and mobile-bearing posterior-stabilized designs had similar posterior condylar translation and tibial axial rotation during weight-bearing deep knee flexion exceeding 120°.

Level of evidence Retrospective comparative study, Level III.

Keywords Total knee arthroplasty · Kinematics · Fixed-bearing · Mobile-bearing

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Introduction

In total knee arthroplasty (TKA), choosing fixed-bearing or mobile-bearing prosthesis has been the subject of argument for many years, and there is still no final conclusion. Mobile-bearing TKAs have been developed as an alternative to fixed-bearing TKAs since the 1970s [9, 10]. Some authors who favour mobile-bearing underlined the mobile-bearing prostheses has much higher articular conformity and greater contact area at the interface between the femoral condyle and polyethylene insert (PI). These characteristics are expected to reduce contact stress and polyethylene wear, and the superiority of mobile-bearing prostheses over fixed-bearing prostheses has been proved by previous in vitro studies [7, 30, 31]. Unfortunately, in vitro studies often do not simulate in vivo conditions because the actuators used to apply joint loads are unable to accurately reproduce in vivo motions, and other studies have found no differences in clinical results including range of motion, clinical score, polyethylene wear and long-term survival between mobile- and fixed-bearing prostheses [8, 16, 19, 20, 23, 34].

Since the 1990 s, videofluoroscopy has been used to assess kinematics of TKAs during various motions and improved the understanding of the kinematic behaviour of the modern total knee replacement[2, 5, 12, 14]. However, very few in vivo studies exist where fixed- and mobile-bearing posterior-stabilized versions of an identical design have been compared [21, 25, 35]. Ranawat et al. [35] in 2004, Delport et al. [12] in 2005, Banks et al. [3] in 2003 and Liu et al. [25] in 2009 reported kinematic analysis of fixed-bearing and mobile-bearing total knee prostheses. However, the postoperative maximum flexion in these studies had great variation, ranged from 70° to 140°, with only few case exceeding 120°. The in vivo kinematics of fixed-bearing and mobile-bearing total knee prostheses remains unclear, particularly for knee flexion over 120°. For racial and cultural reasons, individuals from Asian background often require deep knee bending to do daily activities, such as squatting toilets and sitting cross-legged. Whether for fixed- or mobile-bearing TKA, in vivo motion analyses of flexion over 120° are needed. The purpose of this study was to compare the in vivo kinematics of fixed-bearing and mobile-bearing posterior-stabilized prosthesis during deep knee bending with knee flexion exceeding 120° under weight-bearing conditions using a two- to three-dimensional (2D–3D) registration technique.

Materials and methods

Ten subjects who had undergone clinically successful TKA with mobile-bearing posterior-stabilized prosthesis (PFC-Sigma, Johnson & Johnson/DePuy, Warsaw, IN, USA) and were willing to participate enrolled in the study, the tibial insert of the rotating platform mobile-bearing prosthesis allowed freedom of axial rotation. Inclusion criteria were preoperative diagnosis osteoarthritis, good alignment of the implant with no signs of loosening, no pain at the time of acquisition, Hospital for Special Surgery scores >90 and ability to perform at least 120° of weight-bearing flexion (as measured with a goniometer). To match the mobile-bearing group, 10 patients underwent clinically successful TKA using fixed-bearing posterior-stabilized TKA (PFC-Sigma, Johnson & Johnson/DePuy, Warsaw, IN, USA) with paired age, sex, weight, height during the same period were included in this study, both prostheses had similarly designed femoral components and posterior-stabilized tibial inserts with different contact areas for fixed-bearing and mobile-bearing prostheses (Fig. 1). The demographic data were seen in Table 1. Prior to the study, Institutional Review Board approval from West China Hospital of Sichuan University and informed patient consent was obtained.
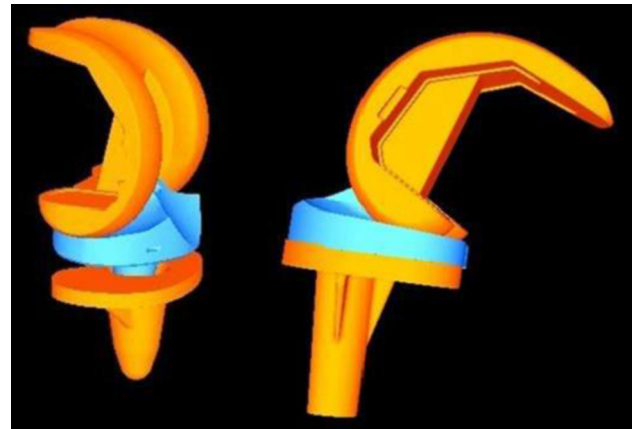

Fig. 1 PFC-Sigma mobile-bearing and fixed-bearing posterior-stabilized prosthesis (DePuy; Johnson and Johnson, Warsaw, IN). Generated by JointTrack (University of Florida)

Table 1 Demographic data of the patients in the two group

	Mobile-bearing TKA	Fixed-bearing TKA	P value
Age [years]	63 (4)	64 (3)	n.s.
Gender [female/male]	4/6	4/6	n.s.
Weight [kg]	65.5 (5.2)	65.1 (3.7)	n.s.
Height [cm]	155.3 (4.2)	156.4 (5.4)	n.s.
Follow-up [months]	16 (5)	16 (4)	n.s.
Postoperative HSS	95 (2)	95 (3)	n.s.
Postoperative maximum flexion (degree)	126 (3)	125 (3)	n.s.

Mean and standard deviations reported

The operation was performed by the same senior surgeon through a standard midline incision with a medial parapatellar arthrotomy. Distal femur bones were firstly cut nearly 9 mm from the most distal normal surface according to intramedullary alignment system with 5° valgus, rotational alignment of the femoral component was decided 3° external rotation with reference to the surgical epicondylar and posterior condylar axes. Secondarily, tibia bones were cut 10 mm from the uninvolved condyle through extramedullary alignment system, perpendicularly to the mechanical axis of tibia in the frontal plane with 5° posterior slope in fixed-bearing prosthesis and 0° posterior slope in mobile-bearing prosthesis in the sagittal plane. The flexion and extension spaces were equalized carefully. After soft tissues were balanced, the tibial and femoral components were implanted, targeting the alignment of these components with the mechanical axis in the frontal plane. Rotational alignment of the tibial component was selected to maximize bone coverage. A tourniquet was used in all patients, and the patella was unresurfaced. All

components were fixed with cement. Postoperatively, all the knees were fitted with a straight Brace. Weight-bearing and knee flexion exercises were started from the first postoperative day. The postoperative rehabilitation programme was the same for both groups. Clinical assessment was performed by using the Hospital for Special Surgery (HSS) score.

Each patient was asked to perform sequential deep knee bending under weight-bearing conditions from extension to maximum flexion under fluoroscopic surveillance in the sagittal plane. Patients were allowed to hold onto a handrail for safety. Successive knee motions were recorded as serial digital X-ray images (20 frames/s, 1024 × 1024 × 12 bits/pixels) using a 12-in digital image intensifier system (AXIOM Artis VB31, Siemens, Germany).

The 3-dimensional position and orientation of the tibial and femoral components were determined using model-based image registration techniques. Calibration and distortion correction parameters were determined using a calibration image of radiopaque beads in known patterns (Camera Calibration Toolbox for Matlab, The Mathworks Inc, Natick, Massachusetts, USA) and were used to correct all trial images. Corrected images and CAD models were imported into open source shape-matching software program (JointTrack, University of Florida) to complete shape-matching process. The automated local optimization algorithm was based on the method described by Mahfouz et al. [26], and the original validation work for the 2D–3D registration technique found that the root-mean-square errors of the relative pose for the femoral component in the tibial component coordinate system were 0.3, 0.4, and 1.5 degree for rotation in the coronal, axial, and sagittal planes, respectively, and 0.2, 0.3, and 0.6 mm for translation perpendicular to the coronal, axial, and sagittal planes, respectively. Preliminary study found that the intraclass correlation coefficients (ICC) of the measurement were 0.94–0.96, which showed a good test–retest reliability. Articular surface separation was declared for any measure >2.4 mm described by Mahoney et al. [27]. The images were analysed at 15 degree intervals according to fluoroscopically measured flexion angles. Knee flexion angles, anterior-posterior (AP) condylar positions, and axial rotation between femoral and tibial components were evaluated. The locations of medial and lateral condylar contacts were estimated as the lowest point on each femoral condyle relative to the transverse plane of the tibial baseplate. The distance between each contact point and the AP centre of the tibial baseplate was measured, Anteroposterior positions of the femoral component anterior to the tibial insert were denoted as positive and the posterior positions as negative. Tibial internal rotation relative to the femur was defined as positive rotation.

Statistical analysis

All data are expressed as mean value (standard deviation). Parametric paired Student's *t* test was used for comparisons between AP displacement of the nearest and contact points on the medial and lateral sides and for comparisons of axial rotational angles between the femoral component relative to the tibial component. Values of $P < 0.05$ were considered statistically significant.

Result

Anteroposterior translation

During the weight-bearing deep knee bending activity, the maximum knee flexion averaged 126° (SD 3) for fixed-bearing knee prosthesis and 125° (SD 3) for mobile-bearing knee prosthesis. There was no significant difference between the two designs (n.s.). From extension to maximum flexion, 8 of 10 (80 %) patients who had a fixed-bearing prosthesis experienced posterior rollback motion of the medial condyle, whereas 6 of 10 (60 %) patients who had a mobile-bearing prosthesis experienced posterior medial condyle motion, 9 of 10 (90 %) patients who had fixed-bearing prosthesis and 10 of 10 (100 %) patients who had mobile-bearing prosthesis experienced posterior femoral rollback of the lateral condyles. No statistically significant difference was detected between the two groups (n.s.). Patients who had fixed-bearing prostheses experienced posterior femoral rollback at a mean of 6.4 mm (SD 1.7) of the lateral condyle, compared with 6.5 mm (SD 2.4) posterior rollback in mobile-bearing prostheses, there was no significant difference between the groups (Figs. 2, 3; n.s.). The posterior femoral rollback of the medial femoral condyle in patients with a fixed-bearing prosthesis was a mean of 1.4 mm (SD 1.6), compared with 0.8 mm (SD 1.2) of posterior movement in patients who had a mobile-bearing prosthesis, there was also no significant different between the groups (Figs. 2, 3; n.s.).

Tibiofemoral rotation

Rotation of the tibia during flexion was measured for each of the two designs tested. During the weight-bearing deep knee bending activity, 9 of 10 (90 %) patients who had a fixed-bearing prosthesis and 10 of 10 (100 %) patients who had mobile-bearing prosthesis experienced medial pivot internal rotation. The mean tibial internal rotation was 7.5° (SD 2.1) for fixed-bearing prosthesis and 9.2° (SD 3.2) for mobile-bearing prosthesis. No significant difference was detected in tibiofemoral rotation between the two designs (Fig. 4; n.s.). The mean rotation at each flexion angle

Fig. 2 a Kinematic pathway of the medial and lateral nearest points for the fixed-bearing prosthesis. **b** Kinematic pathway of the medial and lateral contact points for the mobile-bearing prosthesis
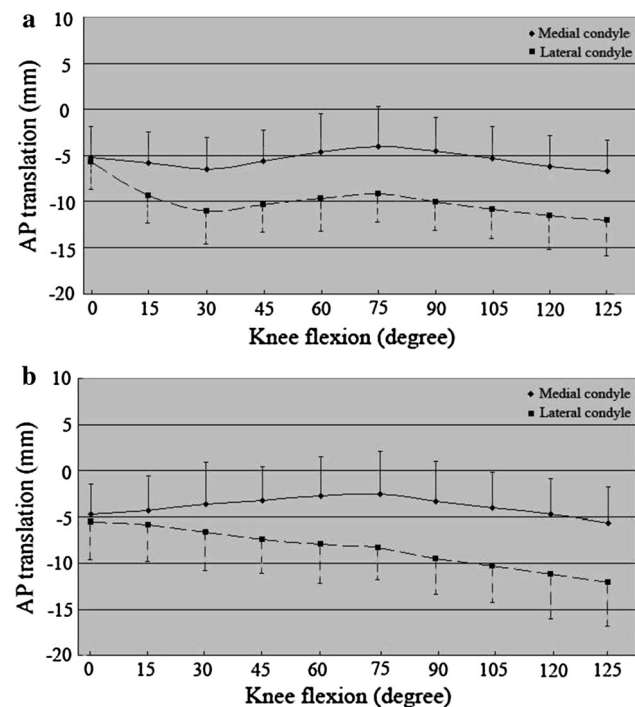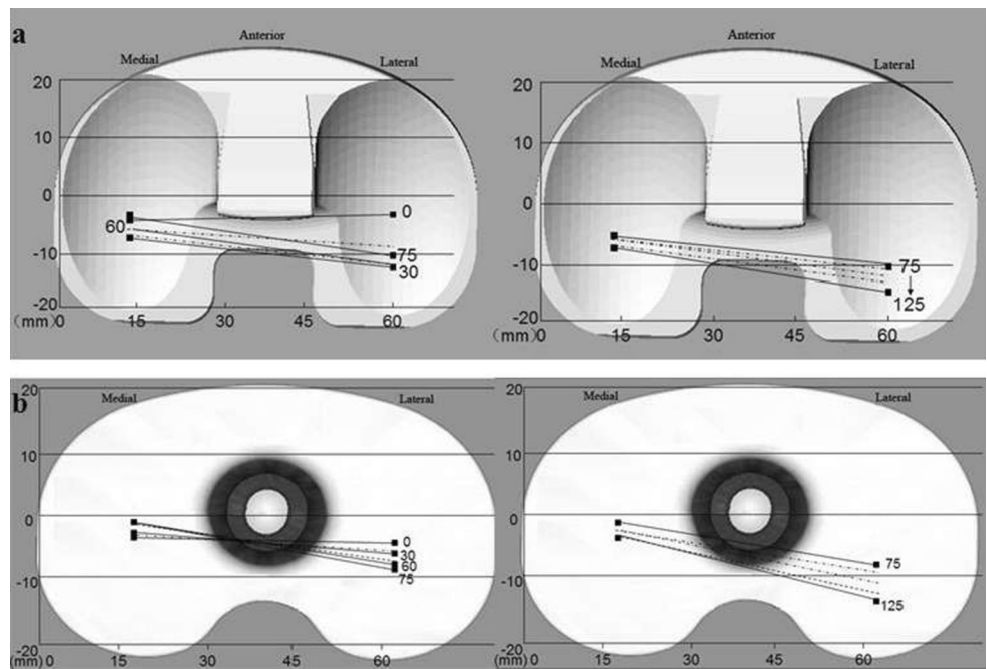

Fig. 3 a Bilateral nearest points between the femoral and tibial component in fixed-bearing prosthesis. The *solid line* shows the medial side, and the *dotted line* shows the lateral side. Positive values indicate anterior. **b** Bilateral contact points between the femoral and tibial component in mobile-bearing prosthesis. The *solid line* shows the medial side, and the *dotted line* shows the lateral side. Positive values indicate anterior
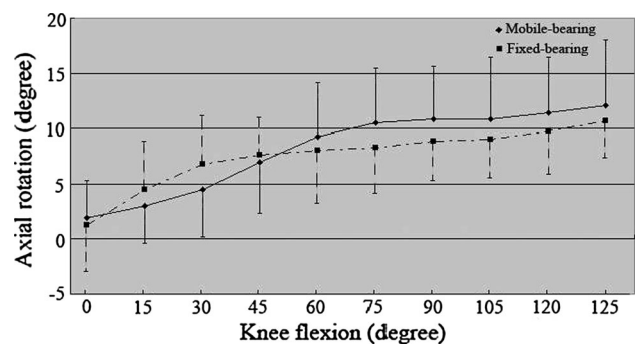

Fig. 4 Axial rotation of the femoral component relative to the tibial tray. The *horizontal scale* shows the flexion angle between the components, and the *vertical scale* shows axial rotation. Positive value represents internal rotation

Discussion

The most important finding of the present study was that both fixed- and mobile-bearing posterior-stabilized knee replacements had similar tibiofemoral kinematic patterns with respect to tibiofemoral translation and axial rotation during weight-bearing deep knee flexion exceeding 120°. The fixed-bearing posterior-stabilized knee replacements demonstrated a relatively asymmetrical posterior femoral translation during flexion with a mean of 1.4 mm for the medial condyle and 6.4 mm for the lateral. Similarly, the mobile-bearing posterior-stabilized knee replacements also demonstrated asymmetrical posterior femoral translation with a mean of 0.8 mm for the medial condyle and 6.5 mm for the lateral. This is less than the maximum amount of posterior femoral rollback in the normal knee [2]. Although

revealed that both groups experienced progressive axial rotation. Lift-off was not identified in any case in any position.

there were no significant difference in the amount of posterior femoral rollback of the medial and lateral condyle between the two designs, the pattern of the medial and lateral condyle motion were different. In mobile-bearing group, the medial condyle experienced anterior motion firstly, then moved posteriorly with progressive knee flexion, and the lateral condyle moved posteriorly during the process of flexion, the anterior motion of medial condyle and posterior translation of lateral condyle illustrate central pivot rotation. This is similar to previously reported results [14, 17, 35]. In the mobile-bearing prostheses, the centrally located trunnion imposed a centrally located pivot point of rotation of the insert on top of the tibial plateau [18, 37]. Futai et al. [17] studied the in vivo kinematics of mobile-bearing prosthesis (PFC-Sigma RPF; DePuy, Warsaw, IN) during deep knee flexion and found that the internal rotation of the tibial component was mostly caused by rotation of the polyethylene insert on the tibial tray, the tibial component typically exhibited a central pivot pattern with -0.7 mm and 5.6 mm of posterior rollback for the medial and lateral condyle, which is similar to the kinematics of mobile-bearing in the present study. Ranawat et al. [35] also reported the mobile-bearing prosthesis experienced anterior motion of the medial condyle and posterior translation of the lateral condyle due to the bearing rotation. However, in fixed-bearing posterior-stabilized prosthesis, the medial and lateral condyles moved posteriorly from extension to 30°, then bilateral condyles moved forward from 30° to 75°, after that the bilateral condyles moved backward until the maximum flexion. Although the post-cam design in posterior-stabilized knee prosthesis was an effective way in preventing the paradoxical anterior motion during the knee flexion, mild forward movement still occured during mid-flexion, similar results were also reported by other researchers [39]. The amount of femoral condyle posterior rollback of the fixed-bearing prosthesis in the present study is in agreement with previous published results. Dennis et al. [13] found that the average amount of posterior femoral rollback of the medial and lateral condyles were -0.9 mm and 7.1 mm. However, Argenson et al. [1] reported that the posterior rollback of the medial and lateral condyles in fixed-bearing posterior-stabilized prosthesis was 8.1 mm and 3.9 mm, which was larger than fixed-bearing in the present study. This may be due to the patient diversity (osteoarthritis and rheumatoid arthritis), pre-operative deformities, muscle adaptations, and the different surgeons [4]. Human factors caused by different surgeon in operation may have some effect on the kinematics after total knee arthroplasty. Victor et al. [39] compared the kinematic outcome of TKA operated by three different surgeons with the same designed total knee prosthesis and surgical technique and found that

there was significant difference in the tibiofemoral movement and tibial axial rotation between different surgeons. On the other hand, several studies found that in vivo knee kinematics after total knee arthroplasty was directly related to the constraints of the design of the prosthesis [5, 6].

In the normal knee, the tibia always had medial pivot internal rotation during knee flexion [2, 22, 24]. This pattern was present in 9 of 10 patients with a fixed-bearing prosthesis and all patients with a mobile-bearing prosthesis, whereas one patient with fixed-bearing prosthesis experienced 3.2° opposite rotation. In the majority of cases, the axial rotation pattern was similar to that of the normal knee, but the extent of rotation was less [2, 22, 24]. Patients who had mobile-bearing prosthesis had 9.2° of normal axial rotation (tibial internal rotation with increasing knee flexion) from extension to maximum knee flexion, which was similar to the results of another mobile-bearing prothesis reported by Tamaki et al. [38]. Compared with the mobile-bearing prosthesis, the fixed-bearing prosthesis had 7.5° of axial rotation, which was less than the former, but there was no significant difference between the two designs (n.s.). In other words, the mobile inserts did not have any obvious advantage in reducing tibial rotational restraint of the knee joint compared to the fixed-bearing design. This confirmed previously reported results. Liu et al. [25] reported that there was no significant difference in tibiofemoral translation and axial rotation between fixed-bearing and mobile-bearing posterior-stabilized total knee prosthesis from squatting to standing. Wolterbeek et al. [40] compared the in vivo kinematics of six different types of knee prostheses including fixed-bearing posterior-stabilized and mobile-bearing posterior-stabilized design during a step-up motion and found that all knees showed comparable axial rotations of the femoral component with respect to the tibial component, the mobile inserts did not add additional mobility to the knee joint compared to the fixed-bearing groups. Most et al. [33] have investigated the kinematics of both the fixed- and mobile-bearing versions of the posterior-stabilized LPS knee (Zimmer Inc., Warsaw, Indiana) in a cadaver model using a robotic testing system (Orthopaedics Biomechanics Laboratory, Harvard Medical School, Boston, Massachusetts), and no significant difference was detected between the two versions and both fixed- and mobile-bearing posterior-stabilized knees only partially restored the posterior femoral translation and axial rotation of the normal knee. Dennis et al. [15] also reported a multicentral videofluoroscopic kinematic analysis of 811 cases, including 103 mobile-bearing posterior-stabilized TKAs and 163 fixed-bearing posterior-stabilized TKAs and found that patients having a mobile-bearing posterior-stabilized TKA experienced

kinematic trends very similar to patients who received the fixed-bearing posterior-stabilized TKA.

However, other studies found that the mobile-bearing design had much greater tibial rotation during knee flexion compared with fixed-bearing design [12, 35]. Ranawat et al. [35] compared kinematics of fixed- and mobile-bearing posterior-stabilized prosthesis and found that the mobile-bearing had greater axial rotation than fixed-bearing implant knee replacements (7.3° vs. 4.1°), but the maximum flexion was only 90°. Delport et al. [12] also reported that the mobile-bearing (Performance; Biomet) had greater tibial internal rotation (7.5° vs. 2.4°) during weight-bearing deep knee bending compared with fixed-bearing prosthesis. However, the analysed postoperative maximum flexion ranged from 60° to 130°, with only few case exceed 120°. Thus, it is difficult to draw any conclusion whether the in vivo kinematics of fixed-bearing and mobile-bearing posterior-stabilized total knee prostheses is different during knee flexion exceeding 120°. Although Shi et al. [36] found that the mobile-bearing prostheses (Nex-Gen LPS-Flex, Zimmer, Warsaw, Ind) had greater tibial internal rotation than fixed-bearing implants during knee flexion exceeding 120°, they took non-weight-bearing and passive knee flexion condition, other studies have confirmed that the kinematics in both posterior cruciate-retaining and posterior-stabilized TKAs under non-weight-bearing passive and weight-bearing conditions were different [41].

A possible limitation of this study is that the difference of tibial cut between the fixed-bearing and mobile-bearing TKAs maybe has some effect on the final outcome. Greater posterior tibial slope should result in a significant increase in maximum flexion by increasing the angle at which impingement occurs either in posterior cruciate ligament (PCL) retaining TKAs or posterior-stabilized TKAs [11, 28, 29, 32]. Meanwhile, greater tibial slope also will alter the laxity of the flexion space, with direct consequence for knee kinematics [3]. This may be the primary cause of tibial axial rotation in fixed-bearing TKAs in this study is different from the result reported by Ranawat et al. [35] with the same posterior-stabilized knee prosthesis during the knee flexion below 90°. The secondary limitation in the present study that warrants consideration is the limited size of the analysis set, with only 20 knees analysed. However, some similar reports have analysed 10–20 knees [3, 35]. Despite of these limitations, the present study provided useful insight into the in vivo kinematics of fixed- and mobile-bearing posterior-stabilized TKAs during a weight-bearing deep knee bending activity, which might be a reference for prosthesis choosing and future development of total knee arthroplasties.

Conclusion

In conclusion, this in vivo kinematic study showed that PFC-Sigma fixed-bearing and mobile-bearing posterior-stabilized designs demonstrated similar posterior condylar translation and tibial axial rotation. Although no direct evidence demonstrated the polyethylene rotation, the central pivot rotation pattern indirectly illustrated the tibial axial rotation was mostly caused by rotation of the polyethylene insert on the tibial tray.

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