—**Original**—

In Vivo Postoperative Motion of Fixed and Mobile Medial Pivot Knees Under Weight-Bearing Conditions after Cruciate-Sacrificing Total Knee Arthroplasty

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Background: In vivo three-dimensional (3D) motion under weight-bearing conditions was analyzed postoperatively in medial pivot cruciate-substituting (CS) knee systems with fixed and mobile inserts.
Methods: Tibiofemoral knee kinematics during squatting were captured with X-ray fluoroscopy for 4 patients in each cohort. The 3D motion of implants was analyzed with KneeMotion motion analysis software (LEXI Corporation; Tokyo, Japan). In addition, anterior-posterior (AP) movement of the distal-most points and the angle of axial rotation of the femoral component on the tibial component were assessed in both cohorts.
Results: Mean AP movement of the femoral component on the tibial component was 3.8±0.5 mm on the medial side and 9.5±0.5 mm on the lateral side in the cohort with fixed prostheses and 5.9±2.1 mm on the medial side and 10.0±2.5 mm on the lateral side in the cohort with mobile prostheses. The mean angle of axial rotation of the femoral component on the tibial component was 14.4±1.1 degrees and 8.2±2.7 degrees of external rotation for fixed knees and mobile knees, respectively.
Conclusions: Postoperative motion analysis confirmed that fixed and mobile CS implants, which have a similar design, guided medial pivot motion under weight-bearing conditions. However, motion differed between these implant types after mid-flexion: bicondylar rollback after medial pivot motion was noted in the mobile cohort. (J Nippon Med Sch 2023; 90: 103–110)

Key words: total knee arthroplasty, cruciate-substituting implant, medial pivot motion, motion analysis

Introduction

The height of the insert lip and high conformity of cruciate-substituting (CS) total knee arthroplasty (TKA) ensure stability, which can be obtained without a post-cam mechanism, regardless of whether the posterior cruciate ligament (PCL) is sacrificed. However, CS knee kinematics under weight-bearing conditions may differ in relation to implant design and insert type. In this study, the in vivo three-dimensional (3D) motion under weight-bearing conditions was analyzed postoperatively in 2 cohorts of medial pivot CS knee systems utilizing different bearing typologies, i.e., those with fixed inserts and those with mobile inserts.

The Advance knee system (MicroPort Orthopedic Inc, Arlington, TN, USA), hereafter referred to as Advance, and the Genus knee system (ADLER ORTHO SPA, Milan, Italy), hereafter referred to as Genus, were chosen as representatives of the fixed and mobile cohorts, respectively. The Advance knee system is a CS implant with good medium- to long-term clinical outcomes[1–4]. It utilizes guided medial pivot motion with a highly congruent medial compartment and a flat lateral compartment. Although some motion analysis studies have been published[5–7], none included a detailed postoperative mo-

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tion analysis during deep knee bending under weight-bearing conditions. The Genus knee system also utilizes guided medial pivot motion, similar to the Advance knee, and has a highly congruent medial compartment. Furthermore, the Genus knee has a mobile insert structure that increases forward and backward movement and reduces shear stress. A review of the literature yielded no motion analysis study of the Genus knee.

After TKA, daily activity exposes knees to numerous movements and loads. Horiuchi et al. noted differences in kinematics under weight-bearing and non-weight-bearing conditions after cruciate-retaining (CR) TKA[8]. Motion analysis studies of knees under weight-bearing conditions will improve understanding of movement during deep knee bending in situations resembling daily activities.

Materials and Methods

This study was approved by the institutional review board (IRB) of Shimura Hospital (IRB number: 2018-2), and informed consent was obtained from all study participants. In total, 124 knees received Advance knee prostheses (fixed CS group) during July 2008 through May 2013, and 154 knees received Genus knee prostheses (mobile CS group) during June 2013 through August 2020. At the final follow-up examination, patients who were able to bend their knee over 130 degrees and to squat or half squat without assistance were enrolled. Ultimately, knee motion was analyzed in 8 knees (4 Advance knees and 4 Genus knees).

Mean postoperative follow-up was 6 years (6 years for all knees) in the Advance group and 4.2 years (range, 2-5 years) in the Genus group. All patients had preoperative grade IV osteoarthritis grade on the Kellgren-Lawrence scale. Mean age was 63.5±1.7 years (range, 62-65 years) in the fixed cohort and 70.8±2.9 years (range, 67-74 years) in the mobile cohort. Mean body mass index was 31.3±2.8 kg/m^2 (range, 28.8-33.7 kg/m^2) in the fixed cohort and 27.6±3.0 kg/m^2 (range, 23.3-29.7 kg/m^2) in the mobile cohort. Average preoperative femorotibial angle was 184.6±4.6 degrees (range, 178-188.6 degrees) in the fixed cohort and 185.3±4.5 degrees (range, 182.3-191.9 degrees) in the mobile cohort. Average preoperative knee range of motion, as determined with a goniometer, was 120±12.2 degrees (range, 105-130 degrees) in the fixed cohort and 125±4.1 degrees (range, 120-130 degrees) in the mobile cohort. Average postoperative knee range of motion was 131±2.5 degrees (range, 130-135 degrees) in the fixed cohort and 138±2.9 degrees (range 135-140 degrees) in the mobile cohort.

Surgical Technique

All surgeries were performed with a conventional medial parapatellar approach and measured resection technique by the same surgeon. In the fixed cohort, the PCL was sacrificed and a medial pivot (MP) insert was used in 1 patient; in the other 3 patients, the PCL was preserved and a double-high (DH) insert was used. In the mobile cohort, the PCL was sacrificed in 1 patient and preserved in 3 patients. PCL sacrifice was indicated when the flexion gap was tighter than the extension gap after bone resection in the measured resection technique. A lateral slide (LS) insert was used for all patients with Genus prostheses. The insert has high medial conformity and a flat lateral surface. The insert within the marker was used in 3 patients with Genus knees.

Motion Analysis

All patients performed as many squats under weight-bearing conditions as possible on an X-ray fluoroscopic table, which was used to record X-ray fluoroscopy images. One squat for each patient was recorded by collecting 6 images per second with a Flat Panel Detector (SONIALVISION G4, SHIMADZU Corporation; Kyoto, Japan) and exported to a computer as frames (i.e., continuous still images). The 3D motion of implants was analyzed with motion analysis software (KneeMotion, LEXI Corporation; Tokyo, Japan; **Fig. 1**), which was able to extrapolate the position of each component by best fitting the superimposition of the X-ray image on a computer-aided design (CAD) model of the implant. This method uses dedicated software that computes implant position in virtual space by exactly matching the implant on the fluoroscopic image, and projects a 3D implant CAD model on the fluoroscopic image[9,10]. The present algorithm was based on the work of Kobayashi et al[11,12]. The mean absolute error of the present system was 1.64 mm in translations and 1.75 degrees in rotations. Analysis of fluoroscopic images allowed us to obtain information on the 3D motion of implants. We evaluated anterior-posterior (AP) movement of the distal-most points and angle of axial rotation of the femoral component on the tibial component. In addition, we evaluated rotational movement of the insert within the marker for 3 patients with Genus knees.

Results

Mean AP distance movement by the femoral component on the tibial component was 3.8±0.5 mm (range, 3.5-4.5 mm) on the medial side and 9.5±0.5 mm (range, 8.9-10.0

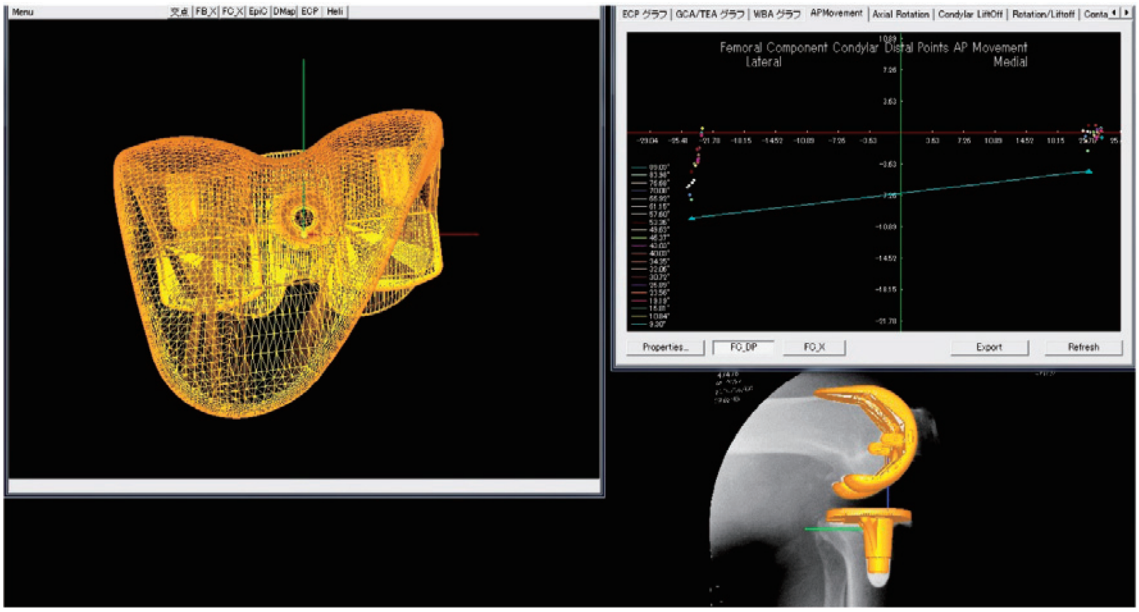

Fig. 1 KneeMotion 3D motion analysis software (LEXI Corporation; Tokyo, Japan).

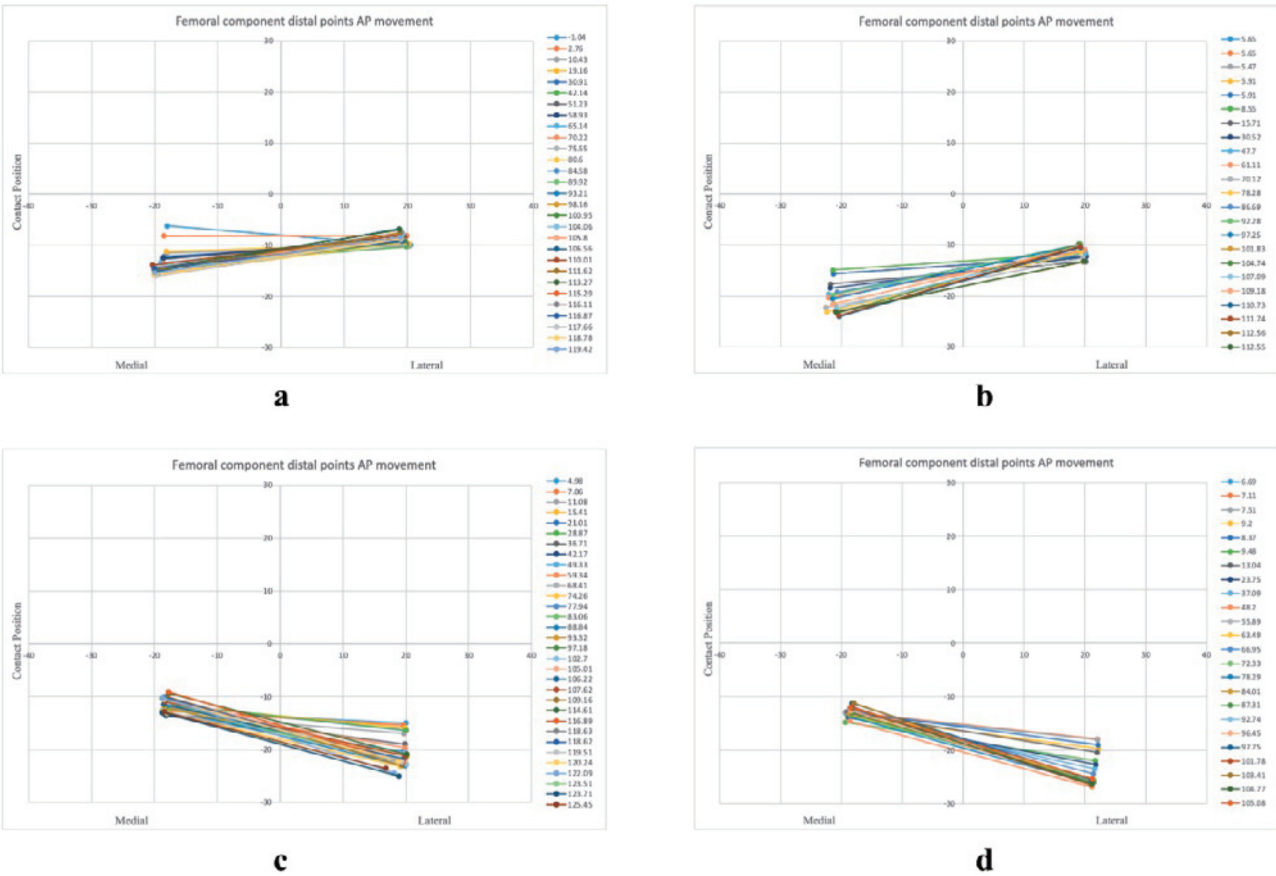

Fig. 2 Anteroposterior (AP) movement of the femoral component on the tibial component in Advance knees (the fixed cohort) (+ anterior, - posterior). One patient who underwent PCL sacrifice had a medial pivot (MP) insert (a), and 3 patients with preserved PCL had double-high (DH) inserts (b, c, and d).
Units: The x and y axes are plotted in millimeters, while, in the legends on the right of each figure, flexion angles during squatting are expressed in degrees.

mm) on the lateral side in the fixed cohort (**Fig. 2**), and 5.9±2.1 mm (range, 3.1-8.0 mm) on the medial side and 10.0±2.5 mm (range, 7.0-12.6 mm) on the lateral side in the mobile cohort (**Fig. 3**). During squatting, the mean

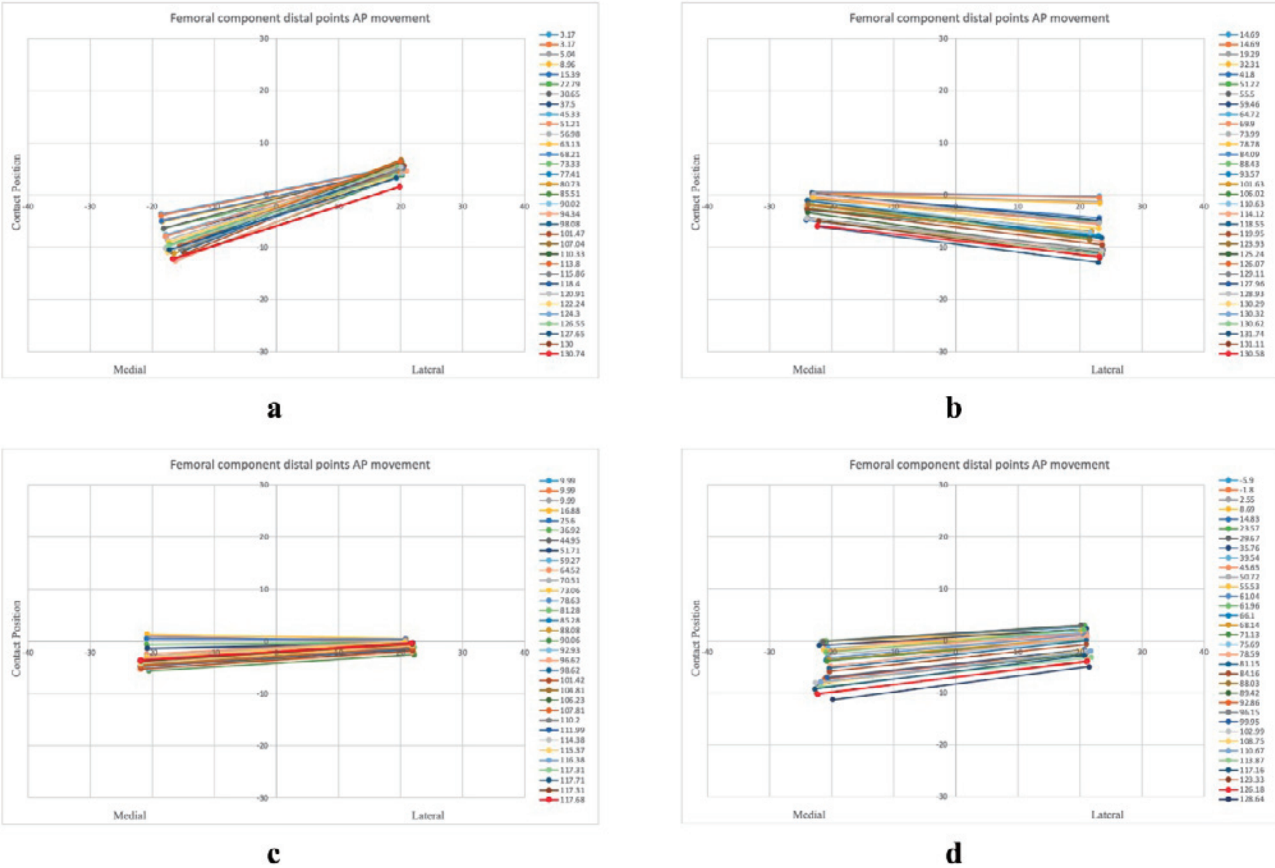

Fig. 3 AP movement of the femoral component on the tibial component in Genus knees (the mobile cohort) (+ anterior, - posterior). One patient underwent PCL sacrifice (a), and 3 had preserved PCL (b, c, and d).
Units: The x and y axes are plotted in millimeters, while, in the legends on the right of each figure, flexion angles during squatting are expressed in degrees.

angle of axial rotation of the femoral component with respect to the tibial component was 14.4±1.1 degrees (range, 13.1-15.6 degrees) of external rotation in the fixed cohort (**Fig. 4**) and 8.2±2.7 degrees (range, 6.0-11.9 degrees) of external rotation in the mobile cohort (**Fig. 5**).

In the fixed cohort, up to mid-flexion, the locus of the distal-most point of the femoral component on the tibial component was a medial pivot motion with almost no medial movement and posterior movement of the lateral condyle. Additionally, from mid-flexion to deep flexion, we noted external rotation in which the medial condyle moved anteriorly and the lateral condyle moved posteriorly. In the mobile cohort, up to mid-flexion, the locus of the distal-most point of the femoral component on the tibial component was a medial pivot motion, as was the case for Advance knees. However, from mid-flexion to deep flexion, we noted bicondylar rollback, in which the medial and lateral condyles moved posteriorly. The insert within the marker rotated externally by approximately 5 degrees from mid-flexion to deep flexion in the patient requiring PCL sacrifice (**Fig. 6-a**). In a PCL-preserved case, the insert within the marker rotated internally by approximately 2 degrees at mid-flexion and then stopped (**Fig. 6-b**). In another PCL-preserved case, the insert did not move during the entire range of flexion (**Fig. 6-c**).

Discussion

The present findings indicate that knee kinematics differ between fixed and mobile insert prostheses during squatting after TKA. Both implants exhibited medial pivot motion, in accordance with their design. However, 1 implant did not show a bicondylar rollback pattern during deep knee flexion. The height of the anterior insert lip substitutes for the function of the PCL in CS TKA, which does not require a post-cam mechanism. The stability and function of CS TKA are similar to those of CR TKA[13,14]. Furthermore, CS TKA prevents paradoxical motion, as seen in CR TKA[15,16], and its high conformity ensures AP stability[17]. The Advance medial pivot knee is a representative model of CS TKA and has good medium- to long-term clinical results[1-4]. In a kinematic study of cadavers, Oomori et al. reported that the MP insert and DH insert

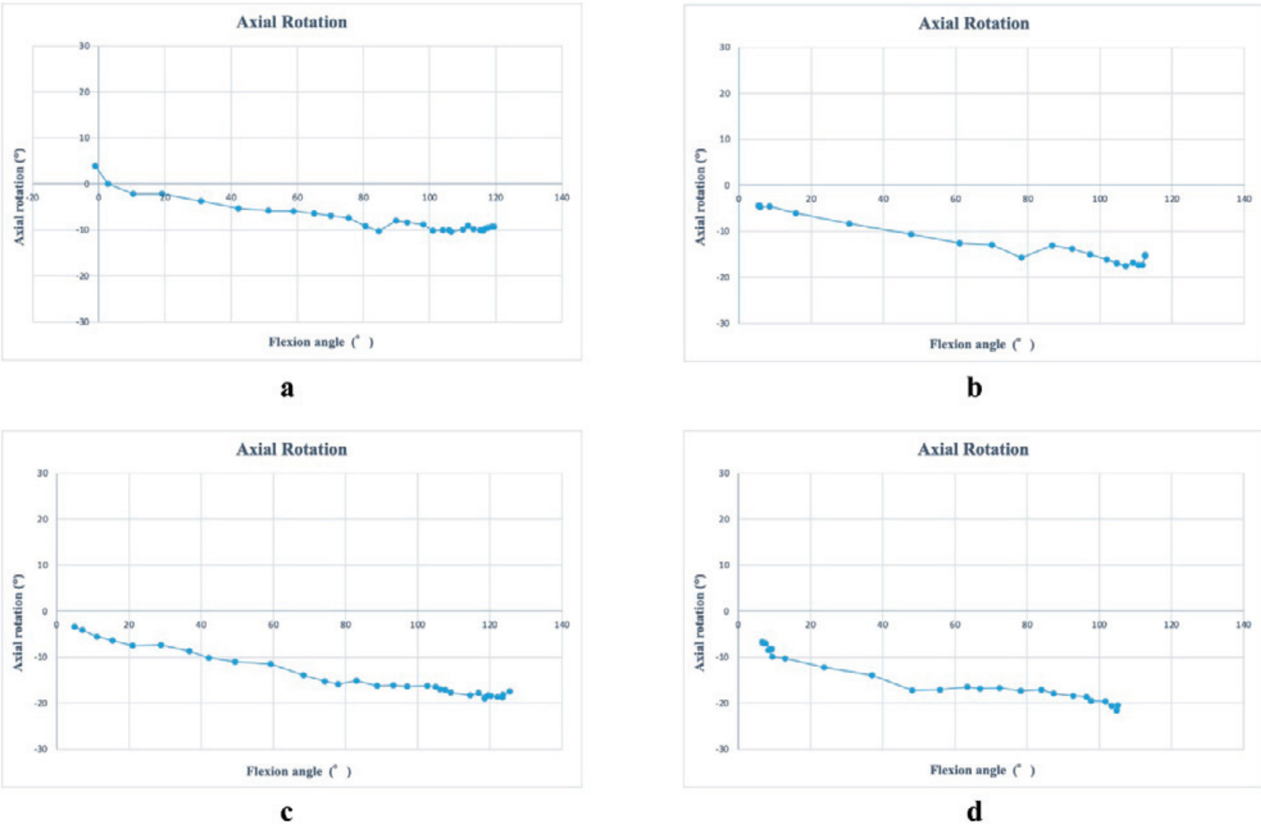

Fig. 4 Axial rotation of the femoral component on the tibial component in Advance knees (the fixed cohort) (+ internal rotation, − external rotation). One patient who underwent PCL sacrifice had a medial pivot (MP) insert (a), and 3 patients with preserved PCL had double-high (DH) inserts (b, c, and d).

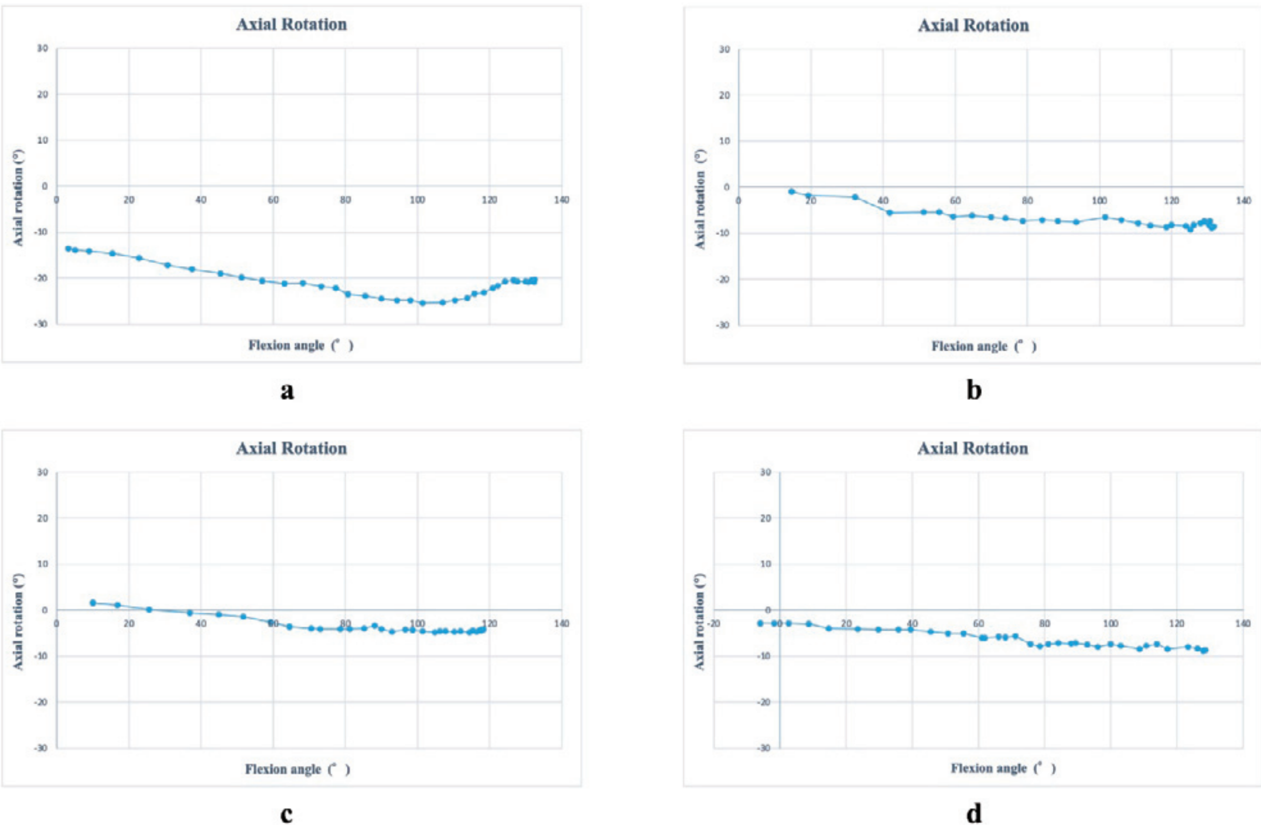

Fig. 5 Axial rotation of the femoral component on the tibial component in Genus knees (the mobile cohort) (+ internal rotation, − external rotation). One patient underwent PCL sacrifice (a), and 3 had preserved PCL (b, c, and d).

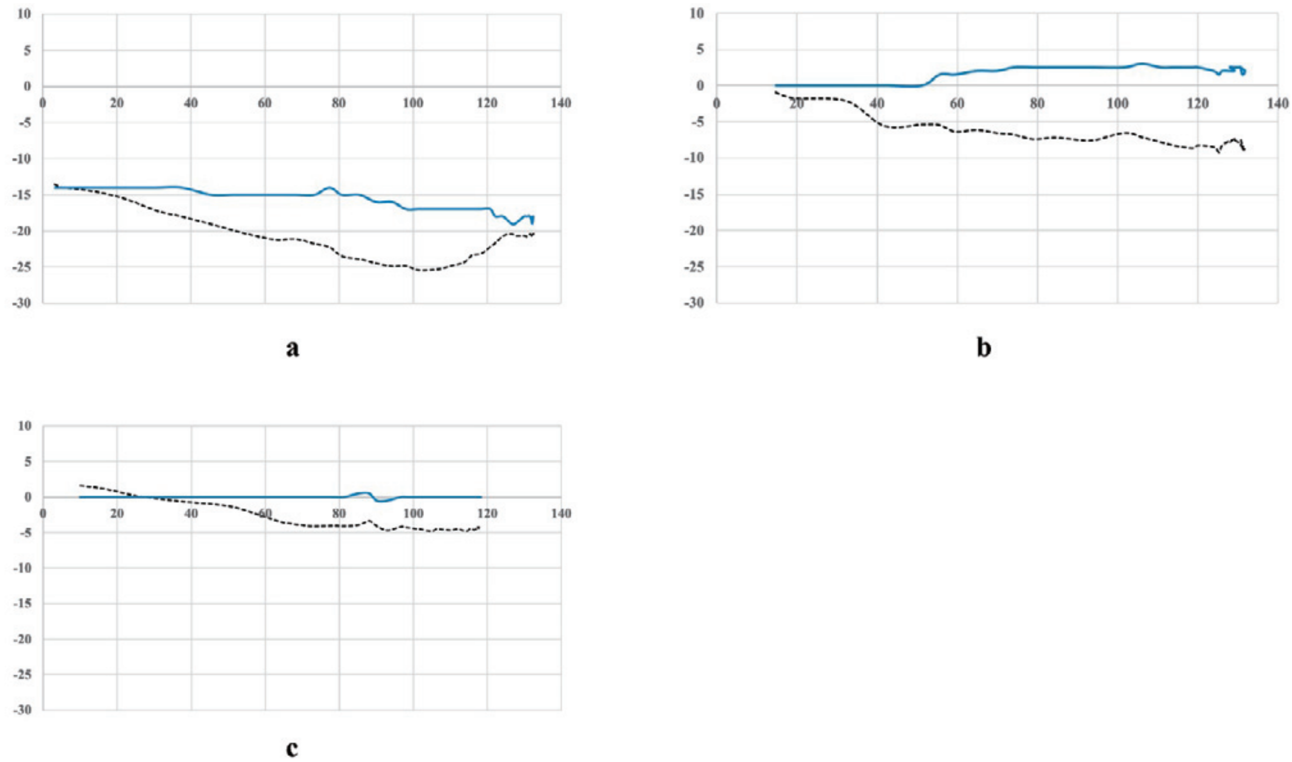

Fig. 6 Axial rotation of the insert within the maker on the tibial component in Genus knees (the mobile cohort) (+ internal rotation, − external rotation). Solid lines show rotational movement of the insert, and dotted lines show rotational movement of the femoral component. One sacrificed PCL case (a), and 2 preserved PCL cases (b and c) are shown.

exhibited bicondylar posterior translation in PCL-preserved cases and medial pivot motion in PCL-sacrificed cases[5]. Miyazaki et al. reported that the medial condyle was almost immobile during flexion and that tibial internal rotation was approximately 4.1 degrees at 100 degrees flexion[6]. Fluoroscopic analysis showed medial pivot motion during the stance phase of gait[7].

In the present study, the locus of the distal-most point of the femoral component on the tibial component was a medial pivot motion with almost no medial movement, and the lateral femoral condyle moved posteriorly up to mid-flexion. During femoral external rotation, the medial femoral condyle moved anteriorly and the lateral femoral condyle moved posteriorly from mid-flexion to deep flexion in the fixed prostheses. This movement was very similar in all 4 patients, regardless of PCL status or insert shape. In the previous cadaveric study[5], the load ratio of quadriceps and hamstring was close to physiological conditions; however, the load was less than that of physiological conditions. In addition, the knee motion differed according to whether the PCL was preserved or sacrificed, but not in relation to insert shape. Subjects may have been more affected by ligament tension than by load in the cadaveric study. Under physiological conditions, subjects were affected by not only quadriceps and hamstrings but also by the iliotibial tract and calf muscle and other muscles. In particular, under weight-bearing conditions subjects were also affected by vertical force exerted by body weight. Therefore, we believe the difference between the present findings and those of Oomori et al.[5] is attributable to the fact that their study used cadavers and was thus not affected by body weight or muscle tone.

A meta-analysis comparing cruciate-substituting ultra-congruent (UC) inserts with posterior-stabilized (PS) inserts reported that clinical outcomes did not significantly differ; however, the UC group had significantly greater external femoral rotation, less posterior femoral translation, greater tibial laxity in the sagittal plane, and less range of motion than the PS insert group[18]. Machhindra et al. reported that UC TKAs had similar functional outcomes and satisfaction, but a smaller motion arc, than mobile-bearing PS TKAs[19]. In contrast, several studies found no differences in clinical outcome or knee flexion between UC TKA and PS TKA[20,21]. A study of intraoperative kinematics found significantly more posterior femoral rollback with the PS insert than with the UC insert; external rotation was similar for the inserts and the native knee during flexion[22]. Furthermore, UC and PS inserts exhibited different intraoperative kinematics, which resulted in less anteroposterior stability and slightly less knee flexion for the UC insert than for the PS insert.

In the present study, movement of the femoral component tended to result in greater external rotation and less posterior translation in fixed prostheses, which was consistent with a report on the UC insert. The present fixed prosthesis was designed so that the distal-most point of the femoral component to the insert was located at a point approximately one-third posterior to the initial position. This may explain why it is difficult to move backward. The present mobile prosthesis was designed so that the distal-most point of the femoral component to the insert was located near the midpoint of the anterior and posterior edge of the insert at its initial position, which is an advantageous shape for posterior translation. In our patients, posterior translation of the femoral component was confirmed even when the insert did not rotate. In the patient who required PCL sacrifice, after mid-flexion, when a posterior drawer force was applied to the tibia, anterior sliding stress was applied to the femoral component. Therefore, the medial compartment of the insert was led anteriorly by the femoral component because the medial compartment had high conformity. Thus, external rotation of the insert was guided. We believe that during the entire movement, rollback of the femoral component was enabled by this adjustment movement of the insert. The present mobile prostheses are therefore more likely than the present fixed prostheses to exhibit rollback movement closer to normal knee motion[23–25], which is advantageous for range of motion during flexion.

This study has some limitations. The first is the small sample size. Because many patients undergoing TKA are elderly, few can safely perform unassisted squats, and the number of such patients is therefore limited. In the present study, we could not perform power analysis because of the lack of data from previous reports. Future studies should enroll a larger number of cases. The second limitation is the difference in flexion angle among patients. Flexion angle depends on the patient squatting without assistance. This is a limitation of in vivo analysis under weight-bearing conditions. The third limitation arises when comparing 2 knee implants that are originally derived from the same design concept (i.e., medial pivot CS knee systems) but have distinct design differences (e.g., mobile and fixed inserts). This study clarified that, even if the original knee concept is the same, the resulting motion is different for the 2 cohorts. The final limitation is that this study includes datasets for both PCL-sacrificed and PCL-preserved procedures, as is clearly stated above.

In conclusion, postoperative motion analysis confirmed that fixed and mobile CS implants, which are similar in design, guided medial pivot motion under weight-bearing conditions. However, the motion of the implants differed after mid-flexion. In the present patients with a mobile CS implant, bicondylar rollback motion was observed after medial pivot motion. Surgeons need to be aware of these implant characteristics before using or selecting implants.

Conflict of Interest: none declared.

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