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Original Article

In Vivo Kinematic Analysis of Mobile-Bearing Unicompartmental Knee Arthroplasty during High Flexion Activities

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Abstract

Mobile-bearing (MB) unicompartmental knee arthroplasty (UKA) has high conformity between the femoral articular surface and the meniscal bearing; therefore, the surface and subsurface contact stress is reduced. Additionally, the survival rate is high. However, the in vivo kinematics of MB UKA knees during high-flexion activities of daily living remain unknown. The aim of this study was to investigate in vivo the three-dimensional kinematics of MB UKA knees during high-flexion activities of daily living. A total of 17 knees of 17 patients who could achieve kneeling after MB UKA were examined. Under fluoroscopy, each patient performed squatting and kneeling motions. To estimate the spatial position and orientation of the knee, a two-dimensional/three-dimensional registration technique was used. We evaluated the femoral rotation and varus–valgus angle relative to the tibia and the anteroposterior translation of the medial sulcus (medial side) and lateral epicondyle (lateral side) of the femur on the plane perpendicular to the tibial mechanical axis in each flexion angle. From 130° to 140° of flexion, the femoral external rotation during squatting was significantly smaller than that during kneeling. Additionally, the medial side of the femur during squatting was significantly more posteriorly located compared with that during kneeling. There was no significant difference between squatting and kneeling in terms of the lateral side of the femur and the varus–valgus position in each flexion angle. At high flexion angle, the kinematics of MB UKA knees may differ depending on the performance.

Keywords
- unicompartmental knee arthroplasty
- kinematics
- high-flexion activities
- mobile-bearing

Recently, several studies have reported that patient's satisfaction with total knee arthroplasty (TKA) is not good.[1–3] However, some studies have reported that patient's satisfaction with unicompartmental knee arthroplasty (UKA) is better than that of TKA.[4,5] This fact suggests that the preservation of the anterior cruciate ligament and the lateral compartment leads to good result. Therefore, it is important to analyze the kinematics of UKA knees to investigate the

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reason. Several studies have examined the kinematics of UKA knees in activities of daily living.[6–9] However, there is no study that compared the kinematics of UKA knees among activities of daily living. Therefore, the presence or absence of a difference in the kinematics of UKA knees in daily activities remains unknown. Furthermore, especially in Asia, people usually bend their knees deeply in daily living such as when sitting on the floor, kneeling, yoga, and praying. Hence, patients desire for high flexion after UKA. Therefore, it is also important to clarify the kinematics of UKA knees during high-flexion activities.

Regarding fixed-bearing (FB) UKA, some studies have demonstrated that the kinematics of the knees after FB UKA replicated the kinematics of normal knees during gait or in vitro.[10–13] However, Mochizuki et al[8] have reported that the kinematics of the knee after FB UKA were not the same as normal during squatting.

Mobile-bearing (MB) UKA has high conformity between the femoral articular surface and the meniscal bearing; therefore, the surface and subsurface contact stress is reduced.[14–18] Pandit et al[19] have reported that the 15-year survival rate of MB UKA was more than 90%. Furthermore, MB UKA knees have been suggested to be superior to FB UKA knees in their restoration of normal tibiofemoral biomechanics.[16,20–22] Moreover, Peersman et al[14] have reported that the kinematics of unloaded MB UKA knees resemble that of normal knees in an in vitro study. However, the in vivo kinematics of MB UKA knees during high-flexion activities of daily living remain unknown.

The aim of this study was to investigate the in vivo three-dimensional (3D) kinematics of MB UKA knees during high-flexion activities of daily living. The hypothesis of this study was that the in vivo kinematics of MB UKA knees differ depending on the high-flexion activities of daily living such as squatting and kneeling.

Materials and Methods

A total of 17 knees of 17 patients who could achieve kneeling after MB UKA (Oxford partial knee; Zimmer Biomet GK, Warsaw, IN) were examined. The patients provided written informed consent to participate in the current investigation. The study has institutional review board approval, with documentation. At the time of fluoroscopic analysis, the mean duration of postoperative follow-up was 9.7 months (standard deviation [SD]: 2.8 months), the mean height was 158.0 cm (SD: 7.7 cm), and the mean body weight was 71.7 kg (SD: 7.0 kg). Of the 17 knees included in the analysis, 8 were contributed by male patients, and the other 9 were by female patients. The new Knee Society scores[23] are reported in ►**Table 1**. All patients had undergone MB UKA to treat medial knee joint osteoarthritis (OA) (Kellgren–Lawrence grade III). The mean hip–knee–ankle angle at the time of analysis was 5.2° (SD: 3.6°). All values were expressed as mean (SD). The radiographic component positions were evaluated according to the Knee Society TKA roentgenography evaluation (►**Fig. 1**).[24] On the anteroposterior (AP) view, the femoral component was set at an angle of 96.8° (SD: 4.3°) and the tibial component was set at an angle of 86.7° (SD: 2.3°) (α and β angles, respectively). On the lateral view, the femoral component was aligned at a flexion angle of 9.3° (SD: 5.1°) and the tibial component was aligned at an angle of 84.7° (SD: 2.7°) (γ and δ angles, respectively).

Under fluoroscopy, each patient performed squatting and kneeling motions at a natural pace (►**Fig. 2**, and ►**Video 1**). The patients practiced the motion several times before recording. The sequential motion was recorded as digital X-ray images (1,024 × 1,024 × 12 bits/pixel, 7.5-Hz serial spot images as a DICOM file) using a 17-inch (43-cm) flat panel detector system (Ultimax-i DREX-U180, Toshiba Medical Systems, Tochigi, Japan; ZEXIRA DREX-ZX80, Toshiba, Tokyo, Japan). Furthermore, all images were processed by dynamic range compression, enabling edge-enhanced images. To estimate spatial position and orientation of the knee, a 2D/3D registration technique was used.[25,26] This technique is based on a contour-based registration algorithm using single-view fluoroscopic images and 3D computer-aided design (CAD) models. We created 3D bone models from computed tomography before surgery, which were used for CAD models (►**Fig. 3**). The estimation accuracy for relative motion between 3D bone models was ≤1° in rotation and ≤1 mm in translation.[26]

Video 1

Fluoroscopic analysis. Each patient performed squatting and kneeling motions under fluoroscopy. Online content including video sequences viewable at: https://www.thieme-connect.com/products/ejournals/html/10.1055/a-2240-3482.

A local coordinate system at the bone model was produced according to a previous study.[26,27] Knee rotations were described using the joint rotational convention of Grood and Suntay.[28] We evaluated the femoral rotation and varus–valgus angle relative to the tibia and the AP translation of the medial sulcus (medial side) and lateral epicondyle (lateral side) of the femur on the plane perpendicular to the tibial mechanical axis in each flexion angle.[26] AP translation

Table 1 The new knee society score after surgery

	Symptoms	Patient satisfaction	Patient expectations	Functional activities
Maximum total points	25	40	15	100
Current study	19.8 (SD: 5.0)	31.0 (SD: 7.0)	8.4 (SD: 1.4)	83.5 (SD: 11.7)

Abbreviation: SD, standard deviation.

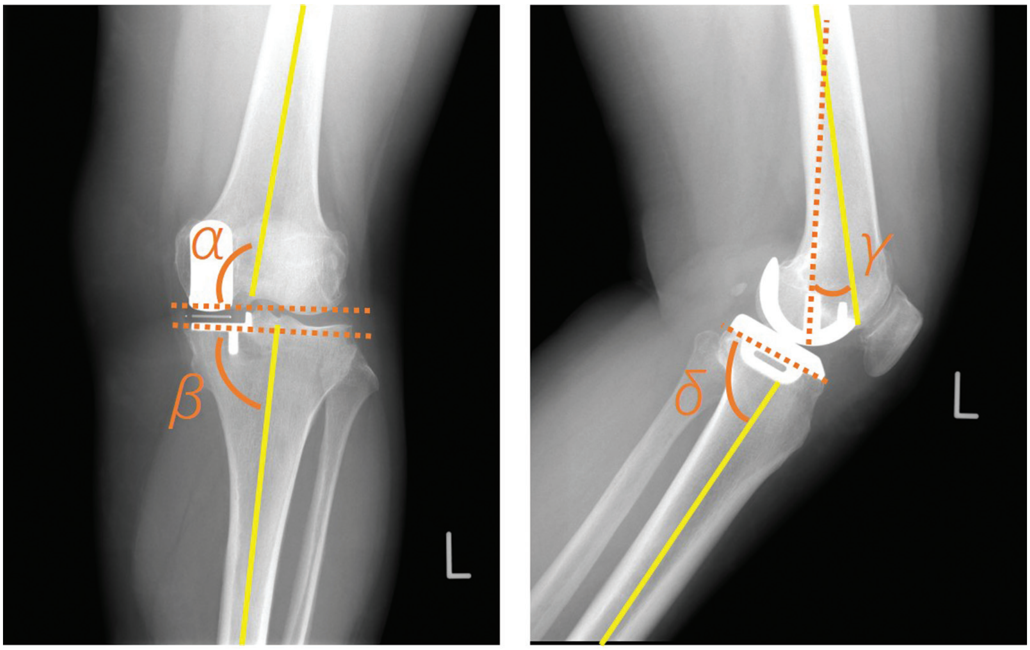

Fig. 1 Radiographic component positions. Alpha (α) angle was defined as the angle between the femoral osseous axis (yellow solid line) and the distal installation line of the femoral component (orange dotted line) on the anteroposterior (AP) view. Beta (β) angle was defined as the angle between the tibial osseous axis (yellow solid line) and the installation line of the tibial component (orange dotted line) on the AP view. Gamma (γ) angle was defined as the angle between the femoral osseous axis (yellow solid line) and the larger peg of the femoral component (orange dotted line) on the lateral view. Delta (δ) angle was defined as the angle between the tibial osseous axis (yellow solid line) and the installation line of the tibial component (orange dotted line) on the lateral view.

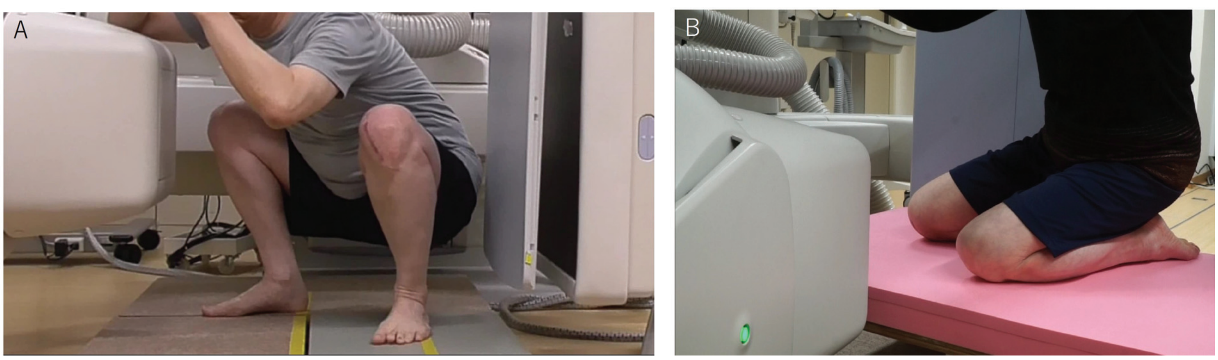

Fig. 2 Fluoroscopic analysis. Each patient performed squatting and kneeling motions under fluoroscopy. (**A**) Squatting motion. (**B**) Kneeling motion.

was calculated as the percentage relative to the proximal AP dimension of the tibia.[26] External and internal rotations were denoted as positive and negative, respectively. Valgus and varus were defined as positive and negative, respectively. The positive and negative values of AP translation were defined as anterior and posterior to the axis of the tibia, respectively.

Statistical Analysis

The results were analyzed using SPSS version 25 (IBM Corp., Armonk, NY). Wilcoxon signed-rank tests were used to analyze the flexion angle between squatting and kneeling. Repeated measures analysis of variance and post-hoc pairwise comparison (Bonferroni test) were used to analyze the differences in rotation angle, varus–valgus angle, and AP translation between squatting and kneeling. A *p*-value <0.05 was considered statistically significant.

A power analysis indicated that 11 patients would be required using EZR[29] when α was set as 0.05 and power at 0.8.

Results

Flexion Angle

During squatting, knees were gradually flexed from 3.3° (SD: 5.2°) to 136.2° (SD: 10.7°). During kneeling, knees were gradually flexed from 102.6° (SD: 8.1°) to 145.1° (SD: 7.3°). The maximum knee flexion angle during squatting was significantly smaller than that during kneeling ($p < 0.001$).

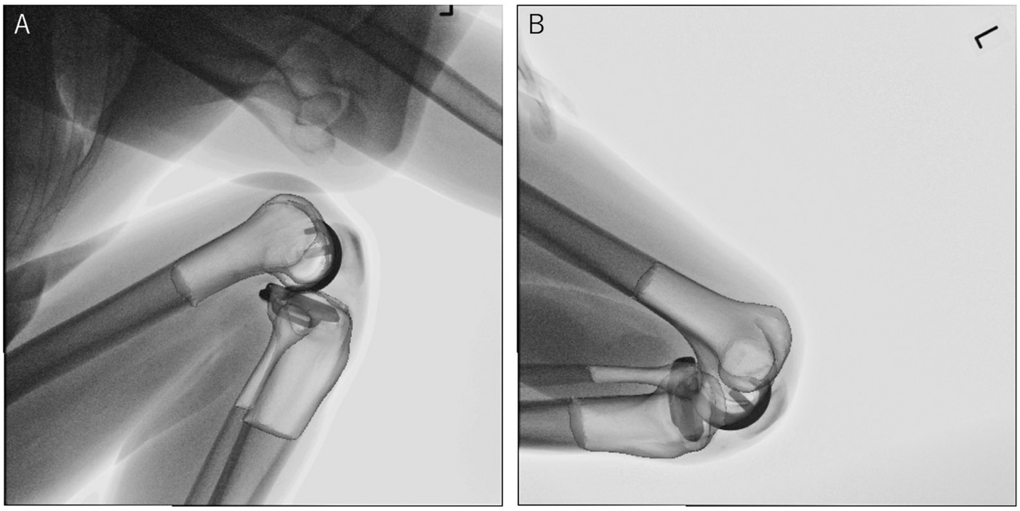

Fig. 3 Two- and three-dimensional registration. Three-dimensional computer-aided design models created from preoperative computed tomography were registered. (**A**) Squatting motion. (**B**) Kneeling motion.

Rotation Angle

During squatting, femurs displayed 12.1° (SD: 5.4°) external rotation relative to the tibia from 0° to 140° of flexion. During kneeling, femurs displayed 6.0° (SD: 5.7°) external rotation relative to the tibia from 110° to 140° of flexion. From 130° to 140° of flexion, the femoral external rotation during squatting was significantly smaller than that during kneeling ($p = 0.01$ respectively) (►**Fig. 4**).

Varus–Valgus Angle

Regarding varus–valgus motion, the knees during both squatting and kneeling did not move significantly ($p = 0.28$ and 0.69). Additionally, there was no significant difference between squatting and kneeling in terms of the varus–valgus position in each flexion angle ($p = 0.39$) (►**Fig. 5**).

AP Translation

During squatting, the AP translation of the medial side indicated 17.6% (SD: 12.5%) posterior movement from 0° to 140° of flexion. During kneeling, it indicated 11.2% (SD: 12.0%) posterior movement from 110° to 140° of flexion. From 130° to 140° of flexion, the medial side of the femur during squatting was significantly more posteriorly located compared with that during kneeling (130° of flexion: $p < 0.001$, 140° of flexion: $p = 0.002$) (►**Fig. 6**).

AP translation of the lateral side of the femur during squatting indicated 50.0% (SD: 14.2%) posterior movement from 0° to 140° of flexion. During kneeling, it indicated 25.1% (SD: 7.1%) posterior movement from 110° to 140° of flexion. There was no significant difference between squatting and kneeling ($p = 0.13$) (►**Fig. 7**).

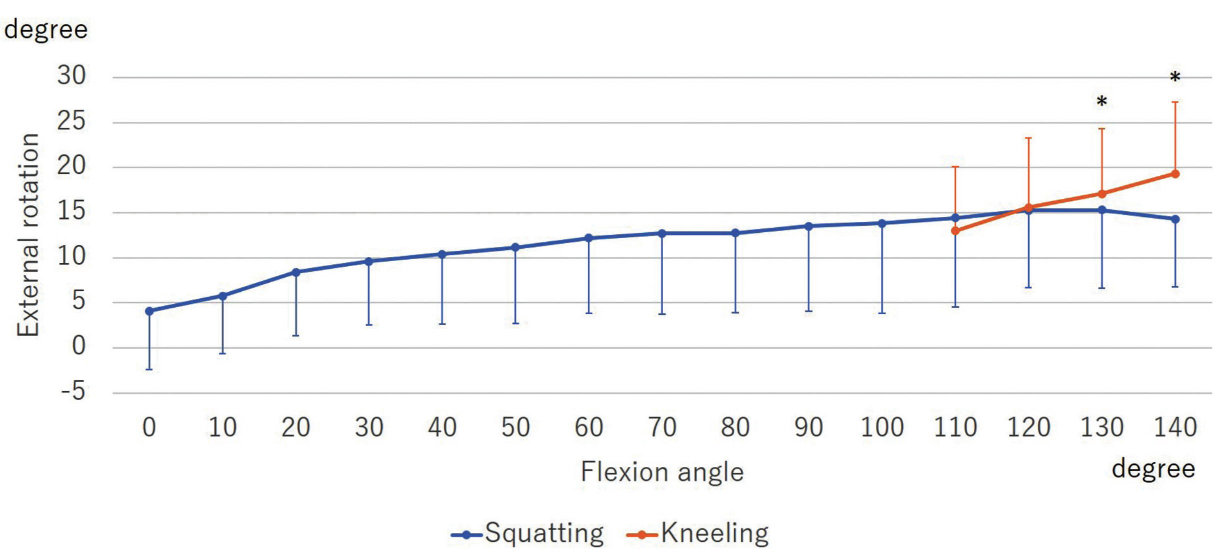

Fig. 4 Rotation angle during squatting and kneeling. Both squatting and kneeling displayed femoral external rotation with flexion. From 130° to 140° of flexion, the femoral external rotation during squatting was significantly smaller than that during kneeling. *Significant differences between squatting and kneeling ($p < 0.05$).

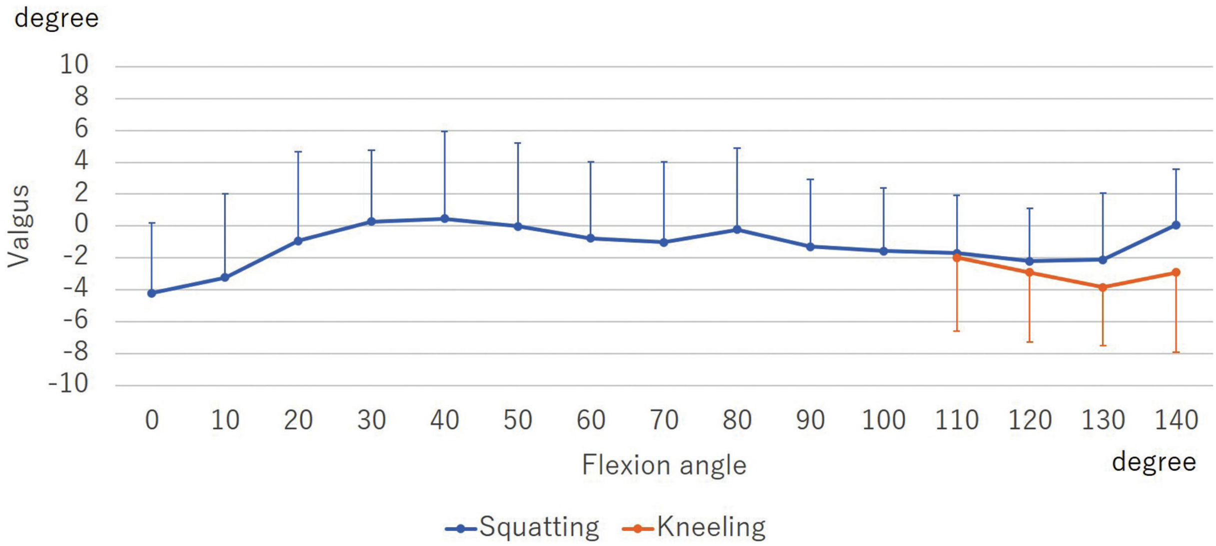

Fig. 5 Varus–valgus angle during squatting and kneeling. Knees during both squatting and kneeling did not move significantly ($p = 0.28$ and 0.69). Additionally, there was no significant difference between squatting and kneeling ($p = 0.39$).

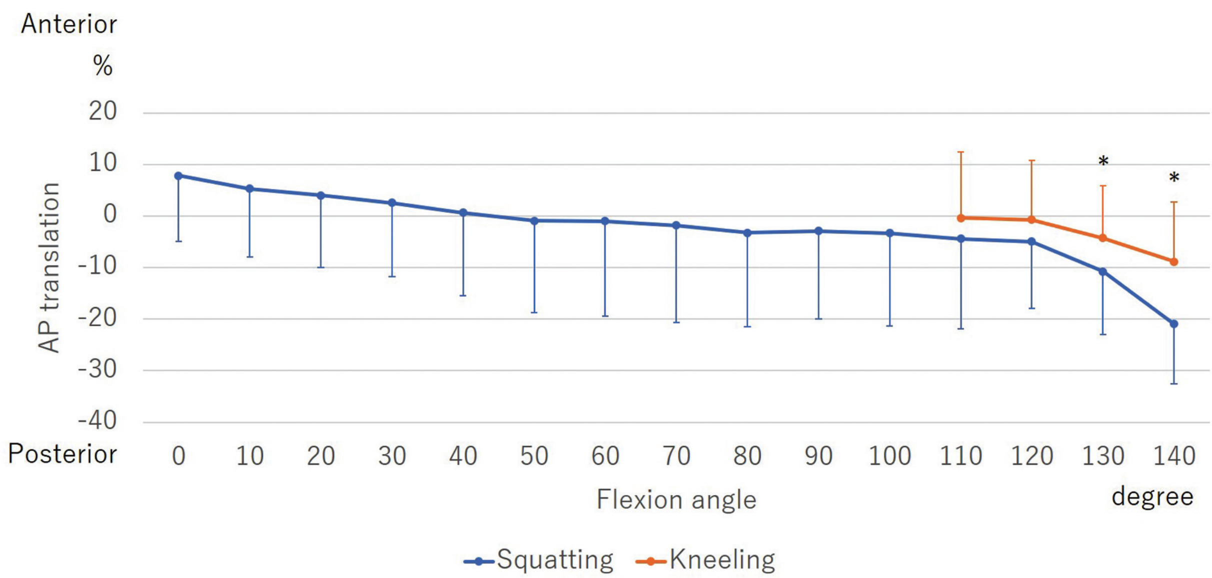

Fig. 6 Anteroposterior (AP) translation of the medial side of the femur during squatting and kneeling. AP translation was calculated as the percentage relative to the AP length of the tibia. Both squatting and kneeling indicated posterior movement with flexion. From 130° to 140° of flexion, the medial side of the femur during squatting was significantly more posteriorly located compared with that during kneeling. *Significant differences between squatting and kneeling ($p < 0.05$).

Discussion

This study has evaluated for the first time the in vivo kinematics of patients after MB UKA during high-flexion activities of daily living using CAD model of fluoroscopically captured images.

At high flexion angle, the femoral external rotation during squatting was smaller than that during kneeling. Furthermore, the medial side of the femur during squatting was more posteriorly located compared with that during kneeling. These suggest that the medial side of the UKA knees more easily slide posteriorly during weight-bearing activity. In this study, the posterior tibial slope of the medial side was 5.3° (SD: 2.7°). Weber et al[30] have demonstrated that a higher posterior tibial slope produced posterior translation of the femur on the medial side of MB UKA knees in the simulation study. Moreover, MB UKA has low conformity between the meniscal bearing and the tibial articular surface due to the flat-on-flat design. The posterior tibial slope and low conformity between the meniscal bearing and the tibial articular surface may affect posterior slide during weight-bearing activity. Meanwhile, the medial side during kneeling did not indicate significant movement with flexion similar to that of normal knees.[26] This suggests that kneeling is a medially stabilized activity which indicates a medial-pivot pattern. During kneeling, the medial contact pressure

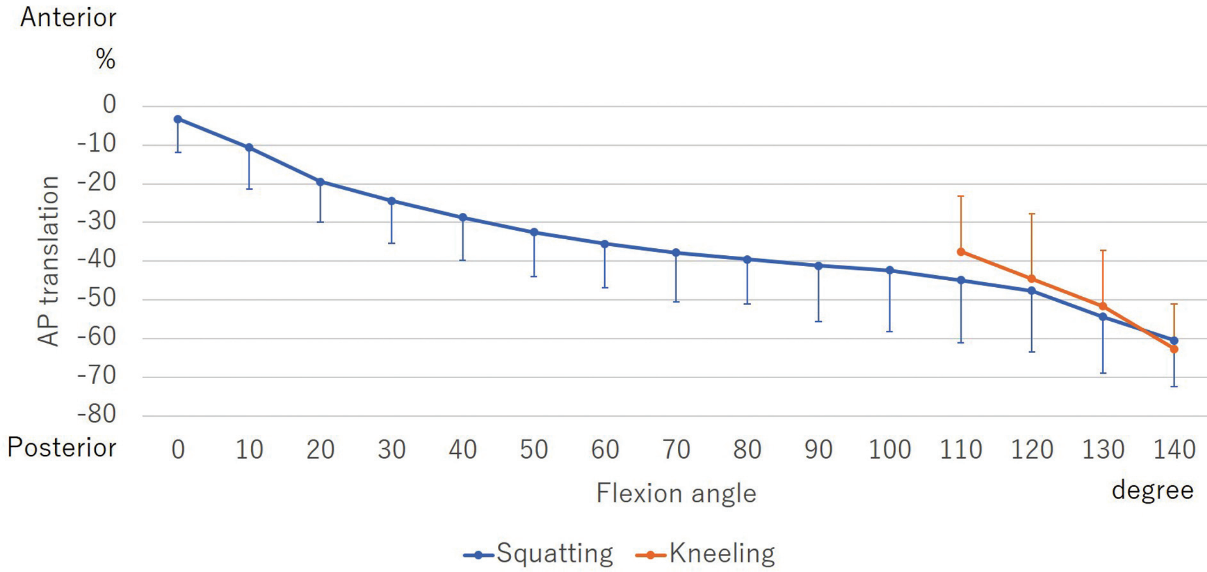

Fig. 7 Anteroposterior (AP) translation of the lateral side of the femur during squatting and kneeling. AP translation was calculated as the percentage relative to AP length of tibia. Both squatting and kneeling indicated posterior movement with flexion. There was no significant difference between squatting and kneeling ($p = 0.13$).

increases.[31] This medial contact pressure might induce the medial-pivot kinematics.

Peersman et al[14] have demonstrated that the in vitro kinematics of unloaded MB UKA knees closely resembled those of normal knees. In normal knees, there are significant differences between squatting and kneeling. Meanwhile, femoral external rotation was more than 20° during both activities.[26] In this study, there were significant differences between squatting and kneeling at high flexion angle, with approximately 10° of femoral rotation during squatting and less than 10° during kneeling. This suggests that the in vivo kinematics of MB UKA knees were also different between squatting and kneeling, similar to the kinematics of normal knees. However, the amount of femoral external rotation with flexion of MB UKA knees might be smaller than that of normal knees. Several studies that investigated the in vivo kinematics of TKA knees during high-flexion activities have reported that the amount of femoral external rotation with flexion of TKA knees was smaller than that of normal knees.[32,33] Additionally, Banks et al[9] have examined the in vivo kinematics of FB UKA knees during lunge and kneeling, and the amount of femoral external rotation was similar to that of the current study. These suggest that the femoral external rotation with flexion of MB UKA knees is similar to those of FB UKA knees and TKA knees. Furthermore, during high-flexion activities, femoral rotation with knees flexion after UKA and TKA is difficult to recreate compared with that of normal knees. Hamai et al[34] have reported that the femoral external rotation of OA knees during high-flexion activities was smaller than that of normal knees due to increased collateral stiffness and other soft tissue contractures. In the current study, there were no significant difference between squatting and kneeling in the lateral side. However, the amount of posterior translation (squatting: 50.0%, kneeling: 25.1%) was smaller than that of normal knees (squatting: 78.7%, kneeling: 40.2%).[26] Therefore, posterolateral stiffness may affect the different kinematics between MB UKA knees and normal knees. Furthermore, Mochizuki et al[8] have reported that the kinematics of FB UKA was similar to that of preoperative knees. These suggest that the kinematics of preoperative OA knees might affect the kinematics of MB UKA knees.

Regarding the varus–valgus angle, there was no significant difference between squatting and kneeling. A previous study has demonstrated that the varus–valgus angle with flexion of normal knees did not differ significantly during squatting and kneeling.[26] This suggests that the varus–valgus kinematics of MB UKA knees may recreate those of normal knees.

The maximum flexion angle of MB UKA knees during kneeling was larger than that during squatting. The maximum flexion angle of MB UKA knees during kneeling was beyond 145°. Regarding TKA, Niki et al[33] have reported that Japanese-style sitting requires beyond 145° of flexion, same with the result of this study. The high-flexion sitting that Asian patients desire after MB UKA may require beyond 145°.

Some limitations of this study need to be discussed. First, this study did not compare between MB UKA and FB UKA. The difference between MB UKA and FB UKA remains unclear. Second, this study analyzed patients who achieved kneeling. The kinematics of patients who cannot perform kneeling might differ. Third, during kneeling, the dorsum of the foot contacted the ground, and the ankle was plantar-flexed. This ankle position might induce greater internal rotation of the tibia which can affect femoral rotation.

Conclusion

In MB UKA, femoral external rotation with flexion was observed during both squatting and kneeling. At high flexion angle, the kinematics may differ depending on the activities.

Conflict of Interest
None declared.

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