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Original article

In vivo kinematic comparison of bi-cruciate retaining total knee arthroplasty between mechanical alignment and functional alignment methods

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ABSTRACT

Background/objective: This study aimed to clarify the kinematics of bi-cruciate-retaining (BCR) total knee arthroplasty (TKA) by comparing the mechanical alignment (MA) and functional alignment (FA) methods and to evaluate differences between the two alignment methods.

Methods: The *in vivo* kinematics of 20 MA TKA and 20 FA TKA knees were investigated under fluoroscopy during squatting using a two-to three-dimensional registration technique. Accordingly, knee flexion angle, axial rotational angle, varus–valgus angle, anteroposterior translation of the medial and lateral low contact points of the femoral component relative to the tibial component and kinematic pathway were evaluated.

Results: No difference in the knee flexion angle was observed between the MA and FA TKA groups. Femoral external rotation was observed in both groups and no significant difference was observed. Significant varus alignment from extension to early flexion range was observed in the FA TKA group. The posterior translation of the medial side was smaller in the FA TKA group than in the MA TKA group. Conversely, no significant difference in the anteroposterior translation of the lateral side was observed. In the kinematic pathway, a medial pivot motion from 0° to 20° of flexion and a lateral pivot motion beyond 20° of flexion were observed in both groups.

Conclusion: During squatting in BCR TKA, the FA TKA group significantly showed varus alignment and smaller posterior translation of the medial side than the MA TKA group from extension to early flexion range.

1. Introduction

Total knee arthroplasty (TKA) is an established treatment for end-stage knee osteoarthritis (OA) and satisfactory clinical outcomes have been reported.[1] To date, the gold standard for TKA alignment is mechanical alignment (MA) and the long-term clinical outcomes and longevity have been reported.[2,3] However, approximately 20 % of patients are unsatisfied with the outcomes.[4,5] Recently, to overcome this dissatisfaction, alternative alignment methods have been introduced.[6,7] The functional alignment (FA) method is one of the alternative alignment methods, in which alignment is determined considering ligament balance using navigation or a robot intraoperatively.[7,8] Chang et al. reported that the FA method achieves balanced mediolateral soft-tissue tension.[8] Another study reported that the FA method aims to restore the native plane and the obliquity of the joint, as dictated by the soft-tissue envelope.[9]

Bi-cruciate retaining (BCR) TKA is a procedure aiming to preserve cruciate ligaments and the outcomes of this procedure have been satisfactory.[10,11] BCR TKA is more ligament-preserving than cruciate-retaining or posterior-stabilised TKA; therefore, the FA method may be a favourable choice as a soft-tissue-preserving technique in BCR TKA. The *in vivo* kinematics of BCR TKA have been reported in MA TKA[12,13]; however, no study has evaluated the kinematics of FA TKA. Additionally, whether the kinematics of BCR TKA would differ between

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the two alignment methods is unknown.

In healthy knees, Bellemans et al. reported a constitutional varus knee alignment.[14] Regarding the *in vivo* kinematics of healthy knees during squatting, the amount of posterior translation of the medial contact point of the knee was small in early flexion range.[15,16]

Therefore, this study aimed to compare the *in vivo* kinematics between MA and FA BCR TKA and to clarify the differences in *in vivo* kinematics between MA and FA TKA. The study hypothesis was that the kinematics of MA and FA TKA would differ and that the kinematics of FA TKA would be closer to native kinematics than those of MA TKA.

2. Materials and methods

This study was approved by our Institutional Review Board [number 10462-(2)] and all patients provided written informed consent. This study was based on 40 knees in 37 patients who underwent BCR TKA at our institution between August 2017 and May 2021. Journey II XR (Smith & Nephew, Memphis, TN) was implanted in all 40 BCR TKAs. Of these, 20 knees in 18 patients were operated using MA BCR TKA between August 2017 and November 2018 and 20 knees in 19 patients were operated using FA BCR TKA between June 2019 and May 2021. The alignment technique (from MA to FA) was changed according to the period. BCR TKA was initially performed using the MA technique in our institution and patient satisfaction was high. However, some patients showed a restricted range of motion and residual lateral laxity of the knee. To achieve better clinical outcomes, we introduced the FA technique[17] in March 2019. The inclusion criteria for this study were as follows: (1) varus knee OA (hip–knee–ankle (HKA) angle <180°) and pre-operative varus deformity <15°; (2) intact cruciate and collateral ligament; (3) pre-operative flexion contracture <15°; (4) primary TKA using the Journey II XR implant; and (5) consent for fluoroscopic evaluation. The exclusion criteria were as follows: (1) valgus knee OA (HKA angle >180°); (2) posttraumatic OA; (3) inflammatory arthritis (e.g. rheumatoid arthritis); (4) revision TKA; and (5) no consent for fluoroscopic evaluation.

Table 1 shows the demographic characteristics of patients undergoing MA TKA and those undergoing FA TKA. All data in this study are expressed as means ± standard deviations. The HKA angle was measured on full-length standing radiographic images. The pre- and post-operative knee extension and flexion angles were measured using a goniometer. No significant difference in pre-operative demographic data was observed between the MA and FA TKA groups. The post-operative HKA angle was significantly varus in the FA TKA group ($p = 0.032$). The radiographic femoral and tibial component positions were evaluated based on the Knee Society's TKA Roentgenographic Evaluation.[18] On the radiographic anteroposterior (AP) view, the α angle of the femoral component and the β angle of the tibial component were measured. On the lateral view, the γ angle of the femoral component and the δ angle of the tibial component were measured. A significant difference in the β angle was observed between the MA and FA TKA groups ($p < 0.001$). Moreover, a significant difference in the timing of fluoroscopic survey was found between the MA and FA TKA groups ($p = 0.048$). The Knee Injury and Osteoarthritis Outcome Score (KOOS)[19] and the 2011 Knee Society Score (2011 KSS)[20] including patient satisfaction were evaluated 1 year after surgery as the patient-reported outcome measures (PROMs) (Table 2). A higher score means better knee condition in both the KOOS and 2011 KSS. Additionally, improvements in the KOOS (post-operative minus pre-operative KOOS) were measured to evaluate improvements in knee condition after surgery (Table 3).

Table 1
Patient demographic characteristics.

	MA TKA (n = 20)	FA TKA (n = 20)	P-values
Sex (female/male)	16/4	16/4	1.000
Age (years)	72.7 ± 6.2	74.5 ± 6.0	0.356
Body height (cm)	156.7 ± 8.6	153.6 ± 8.2	0.264
Body weight (kg)	59.8 ± 7.9	61.0 ± 9.4	0.684
Body mass index (kg/m^2)	24.3 ± 2.4	25.8 ± 3.3	0.126
Pre-operative hip–knee–ankle angle (°)	170.8 ± 4.3	172.9 ± 3.4	0.105
Pre-operative maximum extension (°)	−2.7 ± 2.8	−3.2 ± 2.7	0.579
Pre-operative maximum flexion (°)	129.4 ± 9.1	130.8 ± 8.1	0.631
Post-operative hip–knee–ankle angle (°)	178.5 ± 2.2	177.1 ± 1.5	**0.032**
Post-operative maximum extension (°)	−1.0 ± 2.1	−0.4 ± 1.2	0.292
Post-operative maximum flexion (°)	125.0 ± 6.3	127.0 ± 7.8	0.393
α angle (°)	98.3 ± 1.4	97.7 ± 2.7	0.427
β angle (°)	88.8 ± 1.0	87.3 ± 1.3	**<0.001**
γ angle (°)	1.2 ± 1.0	1.6 ± 0.8	0.157
δ angle (°)	84.8 ± 2.2	84.4 ± 1.5	0.606
Timing of fluoroscopic survey after surgery (months)	9.9 ± 6.1	13.0 ± 2.4	**0.048**

MA, mechanical alignment; FA, functional alignment; TKA, total knee arthroplasty.
Data are presented as means ± standard deviations. The bold type means significant.

2.1. Surgical procedure

All operations were performed by the same surgical team, using the Journey II XR implant and an image-free navigation system (Precision N, Stryker Orthopaedics, Mahwah, NJ, USA). The surgeries were performed using a paramedian approach and the patella was not everted.

2.2. MA TKA

For bone resection, minimum release of medial soft tissue was performed to achieve medial stability as previously described.[17,21] Coronal bone resections of the distal femur and proximal tibia were set to be perpendicular to the mechanical axis. The sagittal alignment of the distal femur was aimed at 4° of flexion. In the sagittal alignment of the proximal tibia, we produced a native slope in patients with a posterior tibial slope of <10°. In patients with a posterior tibial slope of >10°, the tibial cut was reduced not to exceed 10°.[22,23] The amount of posterior femoral resection was adjusted to equalise the extension and flexion gaps of the medial compartment to achieve medial stability. Residual lateral ligamentous laxity was allowed regardless of the extent of the laxity.[24,25]

2.3. FA TKA

FA TKA was performed according to the 'functionally aligned' concept,[8] as previously described.[17] A distal femoral cut was made to

Table 2
Post-operative KOOS and 2011 KSS scores.

	MA TKA (n = 20)	FA TKA (n = 20)	P-values
KOOS			
Pain	85.7 ± 11.9	89.5 ± 9.0	0.277
Symptoms	84.6 ± 10.0	88.9 ± 7.8	0.149
Function in daily living activities	86.3 ± 10.2	90.8 ± 9.8	0.171
Function in sports and recreation	57.5 ± 24.3	66.8 ± 23.7	0.242
Quality of life	71.3 ± 19.3	77.2 ± 17.3	0.338
2011 KSS			
Symptoms	20.2 ± 3.0	21.2 ± 3.4	0.319
Satisfaction	29.3 ± 7.2	31.9 ± 6.7	0.248
Expectation	10.4 ± 2.1	10.9 ± 2.7	0.574
Functional activities	74.3 ± 17.8	80.6 ± 15.7	0.267

KOOS, Knee injury and Osteoarthritis Outcome Score; 2011 KSS, 2011 Knee Society Score; MA, mechanical alignment; FA, functional alignment; TKA, total knee arthroplasty.
Data are presented as means ± standard deviations.

Table 3
Improvement in KOOS scores.

	MA TKA (n = 20)	FA TKA (n = 20)	P-values
Improvement in KOOS			
Pain	36.2 ± 18.7	47.2 ± 19.6	0.074
Symptoms	27.1 ± 17.0	35.7 ± 15.6	0.121
Function in daily living activities	30.1 ± 15.0	34.1 ± 20.5	0.484
Function in sports and recreation	35.3 ± 28.0	39.5 ± 32.2	0.672
Quality of life	44.0 ± 25.3	49.8 ± 26.2	0.503

KOOS, Knee injury and Osteoarthritis Outcome Score; MA, mechanical alignment; FA, functional alignment; TKA, total knee arthroplasty.
Improvement in the KOOS scores is defined as post-operative KOOS scores minus pre-operative KOOS scores.
Data are presented as means ± standard deviations.

reproduce pre-arthritic condyle thickness. Femoral alignment in the sagittal plane was cut similar to that in MA TKA. Then, proximal tibial osteotomy was performed. A distal femoral spaced block mimicking the distal end of the femoral component was placed on the resected distal femur under the condition that the knee was in an extended position. Varus–valgus stress was applied to evaluate the medial and lateral joint laxity under navigation and the amount of proximal tibial cut was decided based on the joint laxity.[17] A sagittal tibial cut was made similar to that in MA TKA. The amount of posterior femoral resection was adjusted to equalise the extension and flexion gaps of the medial and lateral compartments, allowing for slight lateral ligamentous laxity.[26] The slight lateral laxity means a few degrees lateral laxity compared to medial laxity as normal knees.[26]

2.4. Kinematic analysis

For the *in vivo* kinematic evaluation, each patient was instructed to squat under single-view fluoroscopy in the sagittal plane as previously described method.[27] The sequential motion was recorded using digital radiographic images, with a flat panel system same to previous report.[28] A two-dimensional to three-dimensional (2D/3D) registration technique was used to estimate the spatial position and orientation of the femoral and tibial components.[29,30] A local coordinate system (LCS) of the components was established according to a previously described method.[27,29]

The following kinematic parameters were evaluated:

- Knee flexion angle between the femoral and tibial components
- Axial rotational angle of the femoral component relative to the tibial component
- Varus–valgus angle of the femoral component relative to the tibial component
- AP translation of the medial and lateral femorotibial lowest contact points
- Kinematic pathway of the joint surfaces

Knee flexion, femoral rotational angles and varus–valgus angles were calculated according to the previously described method.[31] Knee flexion, external rotation and valgus angles of the femoral component relative to the tibial component were denoted as positive. Positive and negative AP translation values were defined as anterior and posterior locations, respectively, of the femoral component relative to the origin of the LCS of the tibial component.

2.5. Statistical analysis

All statistical analyses were performed using Statistical Package for the Social Sciences (version 25, IBM Corporation, NY, USA). Regarding patient demographic characteristics, Fisher's exact test was used to evaluate sex differences between the MA and FA TKA groups. Differences in other patient demographic characteristics, differences in the KOOS and 2011 KSS and differences in the amount of AP translation between the MA and FA TKA groups were evaluated using unpaired *t*-test. Repeated measures of analysis of variance and post hoc pairwise comparisons (Bonferroni test) were used to evaluate the differences in the rotational and varus–valgus angles and AP position between the MA and FA TKA groups. *P*-values <0.05 were used to denote statistical significance. A priori power analysis was performed using G*Power (version 3.1.9.4; Heinrich Heine University, Düsseldorf, Germany)[32] before this study. Fourteen knees are required to achieve an alpha set, power and effect size of 0.05, 0.8 and 0.25, respectively.

3. Results

3.1. Knee flexion, rotation and varus–valgus angles

In the MA TKA group, the maximum knee extension and flexion angles during squatting were 6.8° ± 7.3° and 109.4° ± 10.5°, respectively. Meanwhile, in the FA TKA group, the maximum knee extension and flexion angles during squatting were 9.6° ± 4.5° and 110.7° ± 17.1°, respectively. No significant difference in both the extension and flexion angles was observed between the MA and FA TKA groups.

Regarding femoral rotation (Fig. 1), femoral external rotation of 4.3° ± 3.0° was observed from 0° to 70° of flexion and beyond 70° of flexion; no significant femoral rotation was observed in the MA TKA group. In the FA TKA group, femoral external rotation of 4.3° ± 2.7° was observed from 0° to 70° of flexion and beyond 70° of flexion; no significant femoral rotation was observed. No significant rotational position was observed at each flexion angle between the MA and FA TKA groups.

Regarding the varus–valgus angle (Fig. 2), the femur showed a valgus change from 0° to 10° of flexion and showed a varus change as the knee flexed in both the MA and FA TKA groups. The FA TKA group showed approximately 1° varus compared with the MA TKA group throughout all flexion ranges. Additionally, the FA TKA group showed a significantly varus alignment compared with the MA TKA group in flexion angles of 0°, 20° and 30°.

3.2. Anteroposterior (AP) translation

For the medial AP translation in the MA TKA group (Fig. 3), the femur showed posterior translation (3.7 ± 1.7 mm) from 0° to 20° of flexion and showed anterior translation (3.5 ± 2.3 mm) from 20° to 100° of flexion. Then, the femur showed posterior translation (1.4 ± 0.8 mm) from 100° to 110° of flexion. In the FA TKA group (Fig. 3), the medial side of the femur showed posterior translation (2.5 ± 1.4 mm) from 0° to 20° of flexion and showed anterior translation (3.8 ± 2.1 mm) from 20° to 90° of flexion. Finally, the femur showed posterior translation (1.5 ± 1.6 mm) from 90° to 110° of flexion. No significant difference in the position of the medial side of the femur at each flexion angle was observed between the MA and FA TKA groups. However, the amount of posterior translation from 0° to 20° of flexion was significantly smaller in the FA TKA group than in the MA TKA group.

For the lateral AP translation in the MA TKA group (Fig. 4), the femur showed posterior translation (7.8 ± 3.0 mm) from 0° to 30° of flexion. Then, the femur showed anterior translation (2.3 ± 2.1 mm) from 50° to 100° of flexion. In the FA TKA group (Fig. 4), the lateral side of the femur showed posterior translation (6.3 ± 2.0 mm) from 0° to 30° of flexion. Then, the femur showed anterior translation (1.7 ± 1.5 mm) from 50° to 90° of flexion and no significant translation was observed beyond 90° of flexion. No significant difference in the position of the lateral side of the femur at each flexion angle was observed between the MA and FA TKA groups. Furthermore, the posterior translation of the lateral side from 0° to 30° of flexion did not differ between the MA and FA TKA groups.

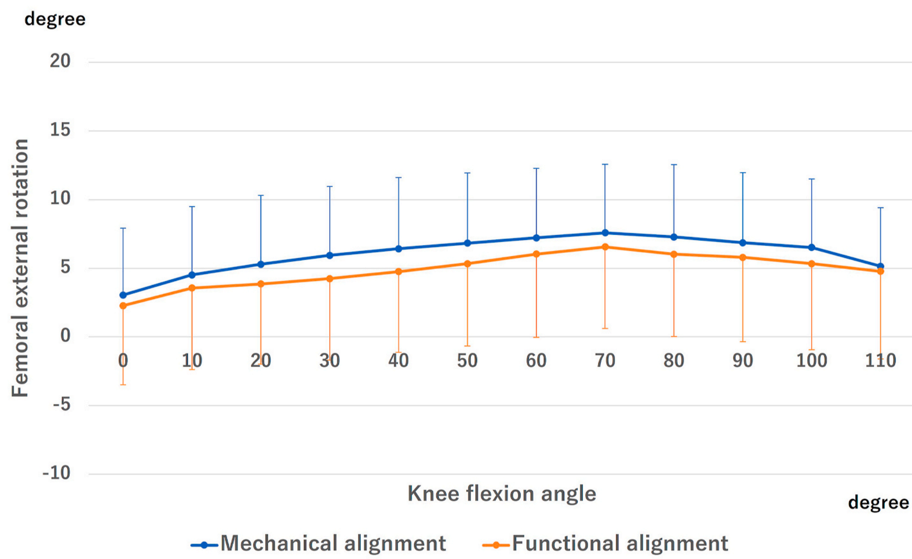

Fig. 1. Femoral external rotational angles. External rotation of the femoral component relative to the tibial component was denoted as positive.

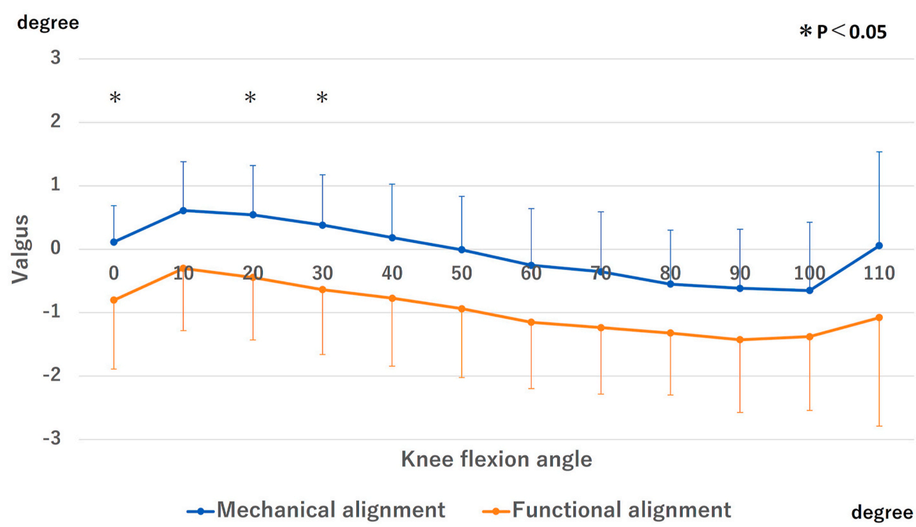

Fig. 2. Varus–valgus angles of the femur. The valgus angle of the femoral component relative to the tibial component was denoted as positive. *Significant differences between the mechanical and functional alignment methods.

3.3. Kinematic pathway

Fig. 5 shows the kinematic pathway of the medial and lateral contact points in the MA TKA group. A medial pivot motion was observed from 0° to 20° of flexion and a lateral pivot motion was observed beyond 20° of flexion.

Fig. 6 shows the kinematic pathway in the FA TKA group. A medial pivot motion was observed from 0° to 20° of flexion and a lateral pivot motion was observed beyond 20° of flexion. The amount of posterior translation of the medial side from 0° to 20° of flexion was smaller in the FA TKA group than in the MA TKA group, as reflected in the medial AP translation (Fig. 3).

4. Discussion

The most important findings of this study were that FA TKA showed significantly more varus alignment than MA TKA from extension to early flexion range. Additionally, the amount of posterior translation of the medial side in FA TKA was significantly smaller than that in MA TKA.

Regarding the varus–valgus angle, FA TKA demonstrated a more varus alignment (approximately 1°) than MA TKA throughout all flexion ranges, as shown in Fig. 2. Additionally, FA TKA showed a significantly varus alignment compared with MA TKA at 0°, 20° and 30° of flexion. The post-operative HKA angle of the FA TKA group was significantly more varus than that of the MA TKA group (FA: 177.1° ± 1.5° *vs*. MA: 178.5° ± 2.2°), even though no significant difference in the pre-operative HKA angles was observed between the FA and MA TKA groups (Table 1). Furthermore, the β angle of the tibial component was significantly smaller (i.e. varus implantation) in the FA TKA group than in the MA TKA group, as shown in Table 1. Intra-operatively, the proximal tibial cutting was planned and executed to aim perpendicular to mechanical axis in the MA TKA group. On the other hand, the cutting was planned and executed according to medio-lateral joint laxity in the FA TKA group, resulted in approximately 3° varus. Therefore, the slight varus implantation due to the FA method and standing radiographic measurement may have influenced the post-operative HKA angle. The concept of constitutional varus knee (HKA ≥3° varus) was advocated by Bellemans et al..[14] Additionally, Riviere et al. reported a patient-specific alignment technique according to the pre-operative anatomy.[33] The FA technique in this study may be a patient-specific alignment technique

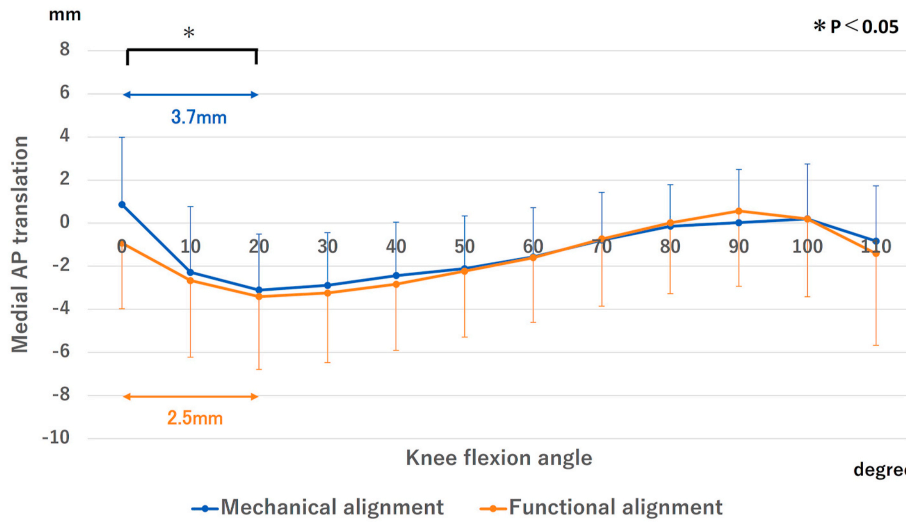

Fig. 3. Anteroposterior (AP) translation of the medial contact point. The anterior translations of the femoral component relative to the tibial component were denoted as positive. *Significant difference in the amount of translation between the mechanical and functional alignment methods.

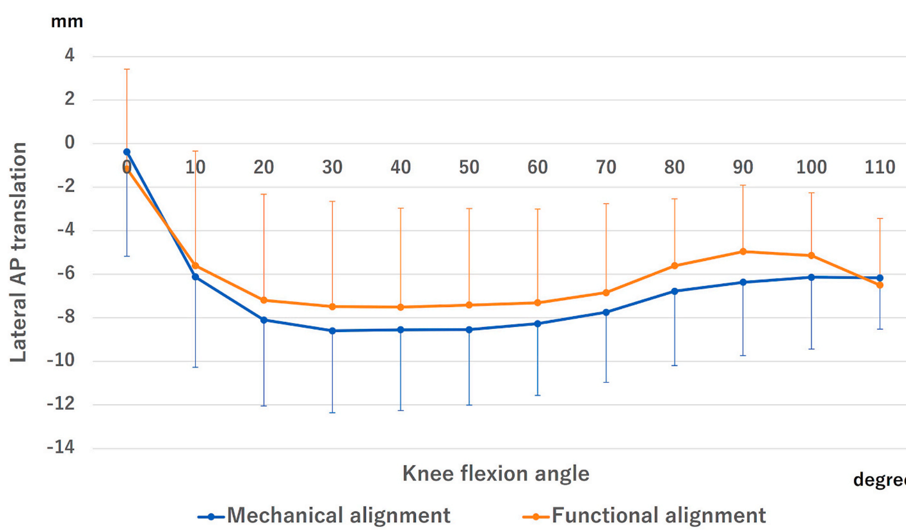

Fig. 4. Anteroposterior (AP) translation of the lateral contact point. The anterior translations of the femoral component relative to the tibial component were denoted as positive.

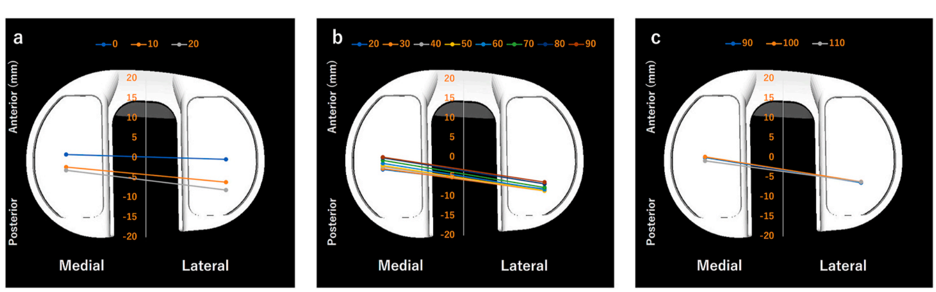

Fig. 5. Kinematic pathways of the joint surfaces in the mechanical alignment method.
(a) From 0° to 20° of flexion.
(b) From 20° to 90° of flexion.
(c) From 90° to 110° of flexion.

that considers the individual ligament balance. An Asian cohort study revealed that healthy adults showed 2.3° ± 2.3° varus knees in the HKA angle and that the percentage of constitutional varus was 35.8 %.[34] In our study, the HKA angle of the FA TKA group was 2.9° varus on average and the absolute PROM values were higher in the FA TKA group than in the MA TKA group although the difference did not reach statistical significance, as shown in Table 2. Therefore, FA TKA may be a more reasonable procedure than MA TKA in terms of reproducing a more

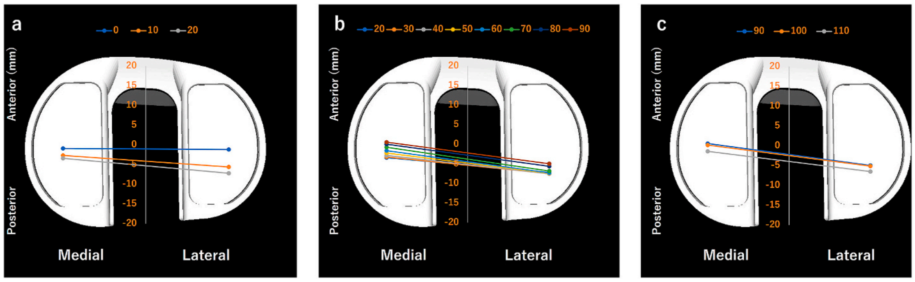

Fig. 6. Kinematic pathways of the joint surfaces in the functional alignment method.
(a) From 0° to 20° of flexion.
(b) From 20° to 90° of flexion.
(c) From 90° to 110° of flexion.

physiological knee.

Regarding medial AP translation, the amount of posterior translation from 0° to 20° of flexion was significantly smaller in FA TKA than in MA TKA. The amount of posterior translation from 0° to 20° of flexion was 2.5 ± 1.4 mm in FA TKA, whereas that in MA TKA was 3.7 ± 1.7 mm, as shown in Fig. 3. Studies have reported the amount of translation of the medial compartment in healthy knees.[15,16,35] Defrate et al. reported that the amount of posterior translation of the medial contact point was 1.9 mm on average from 0° to 30° of flexion during *in vivo* weight-bearing flexion.[16] Additionally, Moro-oka et al. reported that the amount of posterior movement of the medial contact point from 0° to 20° of flexion was approximately 2.5 mm during squatting.[15] Therefore, the amount of medial posterior translation in FA TKA in early flexion may be closer to that in healthy knees than that in MA TKA. Besides, a study on the kinematics of bi-cruciate-stabilised TKA with an anatomical joint surface showed that the smaller the amount of medial posterior translation in early flexion, the better the KOOS score in terms of activities of daily living.[36] Furthermore, in this study, the smaller posterior translation of the medial side in FA TKA may have led to better PROMs than that in MA TKA, although the differences in the PROMs did not reach statistical significance. Regarding PROMs, improvement in the KOOS scores was evaluated in this study (Table 3). In addition to post-operative KOOS scores, improvement in the KOOS scores of the FA TKA group was higher in all subscales than that of the MA TKA group. In particular, the difference in the improvement in the KOOS Pain scores between the FA and MA TKA groups was over 10 points in absolute values, indicating that the improvement in KOOS Pain tended to be higher in the FA TKA group than in the MA TKA group ($p = 0.074$). Recently, medial stability has been reported to be an important factor for improving clinical outcomes in TKA based on clinical and biomechanical studies.[21] Furthermore, the medial stabilising technique and the medial preserving gap technique have been introduced for better soft-tissue balancing and clinical outcomes.[21,37,38] In this study, the smaller posterior translation of the medial side in the FA TKA group may indicate medial stability. Therefore, the FA alignment method in BCR TKA may be a reasonable method to achieve better medial stability and clinical outcomes.

The reason for the kinematic difference in the varus–valgus angle and medial AP translation in early flexion may be due to the difference in the surgical technique between MA and FA TKA. In FA TKA, the varus and valgus stress before tibial bone resection was assessed under the extended knee position. Thus, kinematic differences in early flexion may be observed in this study.

In contrast, no kinematic difference in femoral external rotation and lateral AP translation was observed between MA and FA TKA. Regarding femoral external rotation, the kinematics in MA and FA TKA were comparable (Fig. 1). Kono et al. reported relatively normal kinematics after BCR TKA with an anatomical articular surface (3° inclination of the joint line, medial concave and lateral convex of the tibial surface), even in MA TKA.[39] Because BCR TKA showed relatively normal rotational kinematics in MA TKA, rotational kinematic differences may not be observed in FA TKA. In contrast, rotational kinematic differences were reported between MA TKA and kinematic alignment (KA) TKA in a medial pivot TKA.[40] The authors reported that the amount of femoral external rotation was significantly larger in KA TKA than in MA TKA.[40] This suggests that the rotational kinematic difference between the different alignment techniques may be influenced by the implant design used. Regarding lateral AP translation, no kinematic difference was observed between MA and FA TKA. This may be because the kinematic deviation was relatively large in the lateral AP translation, although the absolute value was large in MA TKA compared with that in FA TKA from 0° to 30° of flexion, as shown in Fig. 4.

Whether the degree of post-operative varus alignment influence the kinematics or not, we carefully reviewed the individual kinematics. However, the change in kinematics regarding varus alignment was not detected in this series. There are two possible reasons for the result. First, the standard deviation of the post-operative alignment (HKA) was small, resulting 2.2° in MA and 1.5° in FA TKA, respectively (Table 1). Second, the number of tested knees was relatively small. It is necessary to investigate the influence of varus alignment in the large number of knees in the future study.

In this study, FA TKA demonstrated a more varus alignment (approximately 1°) than MA TKA throughout all flexion ranges in the varus-valgus angle (Fig. 2). Wherein, we calculated the minimum detectable change (MDC) in the varus-valgus angle and the MDC resulted in 0.17° (Supplementary Table a). Therefore, FA TKA may have shown a significant difference compared with MA TKA at 0°, 20° and 30° of flexion in the varus-valgus kinematics although the difference was approximately only 1° (Fig. 2).

This study has several limitations. First, the timing of the fluoroscopic survey after surgery was different between the MA and FA TKA groups (Table 1). However, the difference was only a few months. Previous studies showed that *in vivo* kinematic changes during the longitudinal examination were small.[41,42] Second, the MA TKA was performed before the KA TKA in terms of period. Therefore, the level of experience in performing the BCR implants could have affected the clinical outcomes. Third, only post-operative *in vivo* kinematics were evaluated in this study. Pre-operative *in vivo* kinematics might influence post-operative kinematics. Fourth, only the kinematics of squatting were evaluated in this study. The results may differ in different activities, such as stair activity or walking. Fifth, the muscle strength of the lower extremity was not evaluated in this study. Differences in muscle strength may influence the kinematics.

5. Conclusion

During squatting in BCR TKA, FA TKA showed a significantly varus alignment compared with MA TKA from extension to early flexion. Additionally, the amount of posterior translation of the medial side was significantly smaller in FA TKA than in MA TKA.

Ethics approval

Approval from the institutional review board was obtained with documentation. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Informed consent

All patients provided written informed consent to participate in this study.

Author contributions statement

ToK contributed to collecting and analyzing the data, writing of the manuscript. KeK, RY and HI designed the study and carried out data curation. TY provided the technical assistance. RY, KoK, RM, TA and TaK collected the data. TT, ShT and SaT provided general support. All authors read and approved the manuscript.

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Declaration of competing interest

The authors have received grants from Smith & Nephew, Stryker outside this study. No author has a conflict of interest regarding the topics discussed in this study.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asmart.2024.09.002.

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