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Original article

Kinematically aligned total knee arthroplasty reproduces more native rollback and laxity than mechanically aligned total knee arthroplasty: A matched pair cadaveric study

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ABSTRACT

Background: A growing body of evidence supports that kinematically aligned (KA) total knee arthroplasty (TKA) provides superior clinical outcomes and satisfaction than mechanically aligned (MA) TKA. In theory, KA TKA would restore knee kinematics closer to the native condition than MA TKA, but the current biomechanical evidence is lacking.
Hypothesis: KA TKA would restore knee biomechanics to the native condition better than MA TKA.
Methods: Seven pairs of cadavers were tested. For each pair, one knee was randomly assigned to KA TKA and the other to MA TKA. During KA TKA, the sizes of femur and tibia resections were equivalent to implant thickness to align with the patient-specific joint line. MA TKA was performed using conventional measured resection techniques. All specimens were mounted on a customized knee-testing system and digitized. Knee motions measured during flexion included rollback, axial tibiofemoral rotation, and laxities, specifically varus-valgus laxity, anterior-posterior translation, and internal-external rotation.
Results: The pattern of knee motion following KA TKA was similar to the native knee. However, following MA TKA, both medial and lateral rollback and tibiofemoral axial rotation were decreased relative to those of the native knee. Valgus laxity was restored only after KA TKA, whereas varus laxity was restored only after MA TKA. Anterior translation was increased regardless of the alignment strategy. In addition, rotational laxities were restored after KA TKA, but external rotation laxity increased after MA TKA.
Conclusion: KA TKA restores femoral rollback and laxity to the native condition better than MA TKA. KA TKA may enhance functional performance and provide a more normal knee sensation.
Level of evidence: II, Controlled laboratory study.

1. Introduction

Advances in implant technology and understanding of knee biomechanics are spurring the ongoing debate about the optimal alignment strategy for total knee arthroplasty (TKA) [1,2]. Over the past few decades, mechanically aligned (MA) TKA, which seeks to achieve neutral alignment and equal soft tissue balance, has been the gold standard approach for modern TKA. However, a growing body of evidence supports the concept that recent modifications in implant design and surgical technique for accurate MA TKA have not improved residual symptoms and functional problems [3]. In addition, during flexion, soft tissue laxity and tibiofemoral joint contact forces in the medial and lateral compartments are not equal in the native knee [4–7]. Moreover, soft tissue imbalance after MA TKA cannot be corrected by collateral ligament release [8,9] Furthermore, neutrally aligned MA TKA does not provide superior survivorship in outliers [10–12] and it may not be the best option for patients with constitutional varus alignment [13,14]. Recently, the kinematic alignment (KA) strategy,

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which targets restoration of patient-specific three-dimensional femorotibial joint alignment and laxity and thereby reproduces more physiologic kinematics by placing implants that reflect individual anatomy, has emerged [1,2,15–17]. Multiple studies report that KA TKA better reproduces patient specific knee anatomy [18–20] and kinematics [5,21–27] and provides superior clinical outcomes and a more normal feeling knee [1,2,19]. In addition, one recent case-series reported that a 10-year survivorship of KA TKA was 97.5% [12]. Nevertheless, appropriate indications for KA TKA and the acceptable safe range for varus implant positioning remain unclear because some patho-anatomy may be biomechanically inferior and therefore clinically deleterious if restored during TKA [28]. In addition, biomechanical evidence to explain why KA TKA provides superior clinical outcomes and patient satisfaction is scarce.

Restoration of close to native knee biomechanics is key to achieving optimal functional performance after TKA, and these biomechanics can be assessed by measuring knee motion during flexion and by comparing postoperative to native knee laxity. Previous studies reported that following KA TKA, femoral rollback and tibiofemoral axial motion during flexion were restored closer to those of the native knee than following MA TKA [22,23,25,29]. On the other hand, as medial and lateral soft tissue laxities and joint contact pressure during flexion are unequal in the native knee [4,6,7], mid-flexion laxity is increased when aiming for an equal gap at 0 and 90° of flexion during MA TKA [9,27]. In addition, KA TKA reproduced more physiologic soft tissue laxities and strains in the collateral ligament [5,21,24,29]. Currently, most studies of postoperative kinematics are based on computational simulation with substantial variations in study design, methodology, and assumptions [22,23,25,30,31]. In addition, judging the effect of the alignment strategy on biomechanics is difficult due to between-study heterogeneity in test conditions, such as patient anatomy and testing jigs. Moreover, biomechanical comparisons between MA and KA TKA performed under similar anatomic preconditions are scarce, and no previous study has evaluated laxities in coronal, sagittal, and axial planes. Therefore, differences between the biomechanical properties of KA and MA TKA remain unclear.

This matched pair cadaveric study determined (1) whether KA TKA achieved knee kinematics, in terms of femoral rollback and tibiofemoral axial rotation during flexion, closer to the native knee than did MA TKA, and (2) whether KA TKA provided more physiologic laxity, specifically varus-valgus laxity, anterior-posterior translation and internal-external rotational laxity, than did MA TKA. To answer these questions, we tested all specimens pre- and postoperatively and compared these two conditions in each alignment strategy. We hypothesized that KA TKA would restore knee kinematics to the preoperative condition better than MA TKA, and would reproduce soft tissue laxity more similar to the preoperative native knee than MA TKA.

2. Materials and methods

Seven pairs of fresh-frozen knees (5 male and 2 female pairs) with a mean age of 65.5 ± 4.0 years (range: 58–70 years) were tested. Because this cadaveric study did not involve human subjects, it was exempt from evaluation by the Institutional Review Board of our institution.

For each cadaver, one knee was randomly assigned to the KA TKA group and the other to the MA TKA group using a computer-generated randomization table permuted into blocks of four and six. All specimens were macroscopically intact and did not exhibit any gross pathology. The specimens were kept frozen at −20 °C until the evening before dissection, at which time they were allowed to thaw at room temperature. The same materials and a validated knee testing system that were used in a previous paper was utilized for this study [26].

All skin and subcutaneous tissue was dissected, leaving the extensor mechanism, retinaculum, knee capsule, and periarticular soft tissues intact. The heads of the quadriceps and hamstring muscles were identified, and eyelets were sutured to each tendon. The fibular heads were fixed to the tibiae with screws, and the fibulae were resected just distal to the proximal tibiofibular joint, thus leaving the lateral collateral ligament insertion intact. The femur was cut 18 cm proximal, and the tibia 20 cm distal, to the joint line. Both ends were anatomically positioned and then potted with plaster of Paris. The knees were securely mounted in anatomical axial alignment on a custom knee-testing system, which permitted physiological muscle loading and six degrees of freedom positioning of both the femur and the tibia. The knee-testing jig was attached to a materials testing machine (Instron Corp., Canton, MA, USA) that was used to adjust the femoral position and knee flexion angle. Each eyelet was attached to a cable that passed through pulleys on a mounting plate affixed to the femoral cylinder; multiple pulleys allowed reproduction of appropriate in vivo muscle force vectors at each knee flexion angle (Fig. 1A) [26,32]. The ratio of the physiological, cross-sectional area-based multiplane loading of the quadriceps and hamstring muscles was used to simulate physiological loading of the knee joint (vastus medialis 51 N, rectus femoris/vastus intermedius 87 N, and vastus lateralis 77 N) and hamstrings (biceps femoris 31 N, semimembranosus/semitendinosus 54 N). The total loading was 300 N [33]. All specimens were tested pre- and postoperatively.

A single senior surgeon (I.J.K) who has operated on more than 2000 primary MA TKAs and 500 KA TKAs performed all surgical procedures using a standard anterior referencing cruciate-retaining (CR) prosthesis instrumentation system (Lospa; Corentec Co. Ltd., Seoul, Korea). The tibial insert design was a high coronal conformity fixed-bearing design without built-in posterior slope. In addition, the femoral component had a single radius axis and the shape and thickness of the medial and lateral portions of the femoral component were symmetric. The thicknesses of the distal and posterior femur implants were 9 mm and 10 mm, respectively. After performing subvastus arthrotomy, the anterior cruciate ligament and both menisci were excised and all patellae were left unresurfaced. In the MA TKA group, TKA was performed using the conventional measured resection technique. Resection of the distal femur was performed using intramedullary instrumentation at a 6° valgus angle and the trans-epicondylar axis (TEA) served as a reference to determine external rotation of the femoral component and for posterior femoral resection. Proximal tibial resection was then performed using extramedullary instrumentation to resect a 10-mm-thick portion of the lateral plateau at a cutting angle 90° to the tibial axis. To establish the tibial slope, the shaft of the extramedullary guide was adjusted so that it was parallel to the long axis of the tibia in the sagittal plane. Finally, the 0 and 90° flexion gaps were measured using a tensor device (KYOWA, Tokyo, Japan). As needed, the tensest fibers of the medial soft tissue were punctured repeatedly with a standard 18-gauge aspiration needle [34]. KA TKA was performed as previously described [18,35]. Briefly, the bone resections were equivalent to the thickness of an implant placed in line with the native joint lines; soft tissue was not released. The thicknesses of all resected bones were measured using calipers, and each resection was adjusted to match the implant thickness. The angle of the tibial resection guide was adjusted until the saw slot and the angle wing were parallel to the coronal and sagittal proximal articular surfaces after compensating for wear [35]. The axial rotation of the tibial component was set parallel to the long axis of the boundary of the lateral tibial condyle. When KA and MA TKA were compared, the resected bone thickness

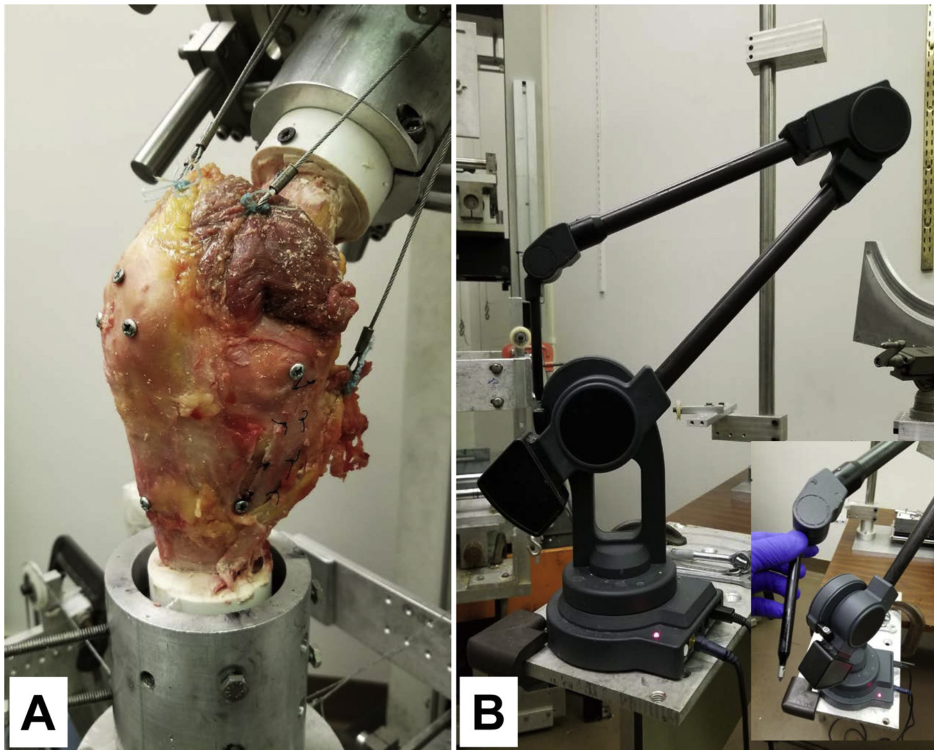

Fig. 1. Custom knee testing system with six degrees-of-freedom (A) and a Microscribe 3DLX 3 dimensional digitizing instrument (B).

Table 1
Resected bone thicknesses (mm) after KA TKA and MA TKA.

	KA TKA (n = 7)	MA TKA (n = 7)	p-value
Distal femur			
Medial	9.7 (0.4)	10.9 (0.9)	< 0.01
Lateral	10.1 (0.4)	6.9 (0.6)	< 0.01
Posterior femur			
Medial	11.1 (0.6)	13.3 (1.5)	< 0.01
Lateral	11.6 (0.5)	9.4 (1.5)	< 0.01
Tibia			
Medial	8.1 (0.6)	2.0 (0.3)	< 0.01
Lateral	8.4 (0.4)	9.7 (0.6)	< 0.01

Data are presented as means (standard deviation). KA: kinematically aligned; MA: mechanically aligned; TKA: total knee arthroplasty.

of the distal and posterior femur and tibia differed substantially (Table 1).

Knee kinematics were evaluated at knee flexion angles of 0, 30, 60, and 90°. A consistent protocol utilizing anatomical landmarks was employed by placing three digitizing markers on each patella, femur, and tibia for a total of nine markers. The femoral and tibial anatomical reference system included the TEA for the medio-lateral (ML) axis of the femur and the trans-tibial axis (TTA), which is the longest ML axis of the tibia connecting medial and lateral anatomical digitizing markers. Kinematic data were collected using a MicroScribe 3DLX 3-dimensional digitizing instrument (Revware Inc., Raleigh, NC, USA), which digitized the coordinates of 9 markers in 3-dimensional space (Fig. 1B). Each measurement was performed in duplicate. Repeatability was checked and a third trial was performed if the difference between the first two trials was > 1 mm; the mean values between the two trials were used. Knee kinematics were assessed by measuring the medial and lateral femoral rollback and the tibiofemoral axial rotation during flexion. The medial and lateral rollback was calculated as the backward movement of each medial and lateral femoral epicondyle during flexion on the transverse plane of tibia. Tibiofemoral axial rotation during flexion was calculated as external rotation of the TTA relative to the TEA. Because defining the physiologic neutral position of the cadaveric knee is inherently challenging, laxity measurements were defined as the resultant varus-valgus angular displacement, anterior-posterior (AP) displacement, and internal-external rotational displacement of the tibia relative to the femur when a 60-N load was applied [36]. To quantify varus and valgus laxity, MicroScribe measurements were obtained with a 60-N of load applied to the varus and then the valgus direction. To assess AP translation, a 60-N of load was directed anteriorly then posteriorly. For rotational laxity, 60 N was applied to produce internal rotation then external rotation.

2.1. Statistical analysis

All data are presented as means with standard deviations. All values obtained at each tested flexion angle were converted into differences from the value at full extension; these corrected values were then compared. The Mann–Whitney U test was employed to compare the resected bone thicknesses between KA and MA TKA knees, and all differences between native and prosthetic knees. All computations were performed using SPSS for Windows software (ver. 21.0; IBM Corp., Armonk, NY, USA); a P-value < 0.05 was considered to indicate statistical significance.

A priori power analysis based on the results of previous biomechanical studies regarding changes of biomechanics after TKA was performed to determine the necessary sample size needed for sufficient statistical power [26,37]. Using the two-sided hypothesis test at an alpha level of 0.05 and a power of 80%, it was found that seven pairs of knees were required to detect a 2° and 1-mm differences. These values were considered biomechanically meaningful because typical differences in thickness between sizes of femoral component and polyethylene are 1–2 mm in currently available TKA implants and increasing the polyethylene thickness by 2 mm caused substantial imbalance [38].

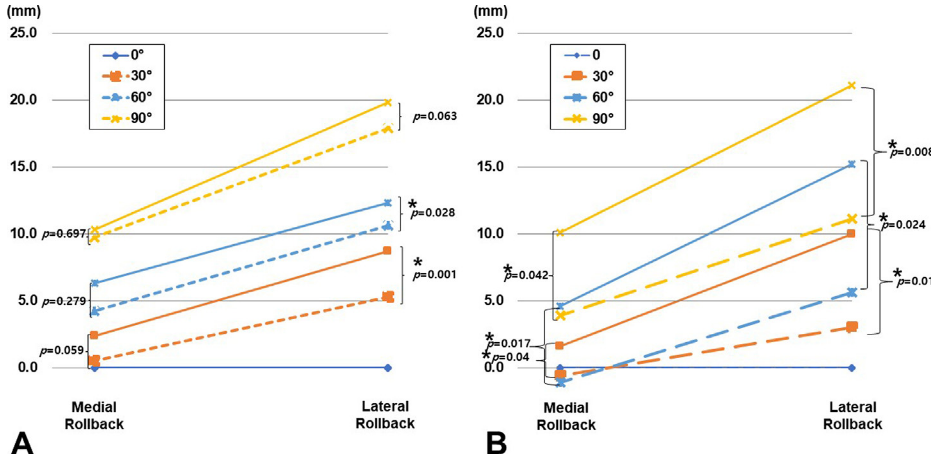

Fig. 2. After kinematically aligned (KA) total knee arthroplasty (TKA), medial rollback is similar to that of the native knee (A). After mechanically aligned (MA) TKA, medial rollback is less than that of the native knee at all flexion angles (B). Lateral rollback decreases after both alignment strategies. Data are presented as means. Line colors reflect the flexion angle. Solid lines indicate the native knees: short dotted lines indicate the knees after KA TKA, and long dotted lines indicate knees after MA TKA. Significant differences ($p < 0.05$) are marked with asterisks.

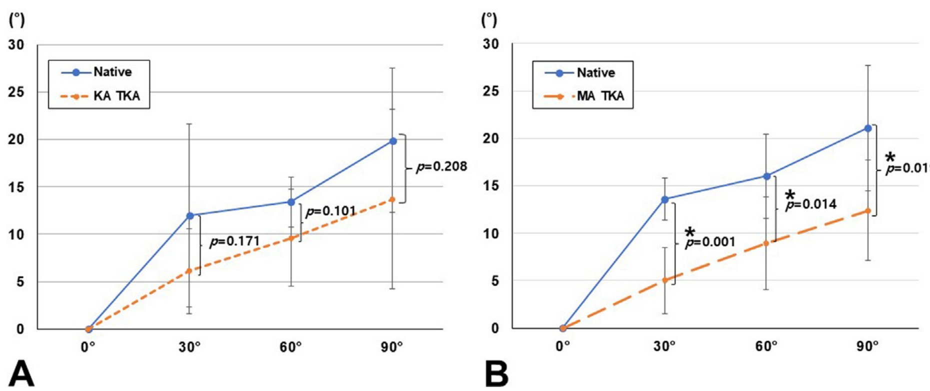

Fig. 3. The pattern of tibiofemoral axial rotation (*y*-axis) during knee flexion after KA TKA do not differ significantly from that of the native knee (A), but that after MA TKA is significantly less than the native knee at all flexion angles (*x*-axis) (B). The error bars indicate standard deviation. Solid lines indicate the native knees: short dotted lines indicate the knees after KA TKA, and long dotted lines indicate knees after MA TKA. Significant differences ($p < 0.05$) are marked with asterisks.

3. Results

KA TKA achieved femoral rollback and tibiofemoral axial rotation during flexion that was closer to the native knee than did MA TKA. After KA TKA, lateral rollback at $\leq 60^\circ$ of flexion was less than that of the native knee; however, medial rollback was similar to the native knee at all flexion angles (Fig. 2A). In contrast, after MA TKA, both medial and lateral rollback were significantly less than those of the native knee throughout the entire range of flexion. Notably, the femur moved anteriorly at $\leq 60^\circ$ of flexion (Fig. 2B). Additionally, tibiofemoral axial rotation during flexion after KA TKA did not differ significantly from the native knee (Fig. 3A), but after MA TKA they were significantly less than those of the native knee at all flexion angles (Fig. 3B).

KA TKA achieved greater restoration of valgus laxity and both internal and external rotation laxities relative to the native knee. After KA TKA, valgus laxity was similar to the native knee but varus laxity increased (Fig. 4A). On the contrary, varus laxity after MA TKA was similar to the native knee but valgus laxity increased (Fig. 4B). After both KA and MA TKA, anterior translation laxities were greater than those of the native knee, whereas posterior laxities were similar to the native knee (Fig. 5). Internal and external rotational laxities after KA TKA were similar to those of the native knee at all flexion angles (Fig. 6A), but external rotation laxities after MA TKA were greater than that of the native knee at $\leq 60^\circ$ of flexion (Fig. 6B).

All these results are summarized in the electronic appendix.

4. Discussion

A growing body of evidence suggests that modification of the traditional MA TKA approach towards a more native alignment with preservation of soft tissue laxity is required to achieve better functional performance after TKA [39,40]. Recently, the KA strategy, which targets restoration of patient-specific alignment and laxity, has emerged and 10-year clinical outcomes and survivorship after KA TKA seem promising [12]. However, the lack of biomechanical comparisons between MA and KA TKA limits our understanding of why KA TKA achieves more physiologic biomechanics and superior satisfaction than MA TKA.

This study demonstrated that KA TKA achieved knee kinematics closer to the native knee than did MA TKA. In this study, the pattern of femoral rollback and tibiofemoral axial motion during flexion after KA TKA was similar to those of the native knee, but after MA TKA, a remarkable paradoxical anterior translation of the femur was observed at $\leq 60^\circ$ of flexion. Our hypothesis is confirmed. The results of this study are similar to previous in-silico studies that reported excellent restoration of femoral rollback and axial rotational motion after KA TKA [22,23,25]. In addition, our findings agree with a comparative cadaveric study that reported that after KA TKA, postoperative knee kinematics were restored closer to those of the native knee than after MA TKA [29]. Because we conducted a matched pair study using the same implant, postoperative knee kinematics in this study were primarily affected by the alignment strategy. The difference we observed may be attributable to

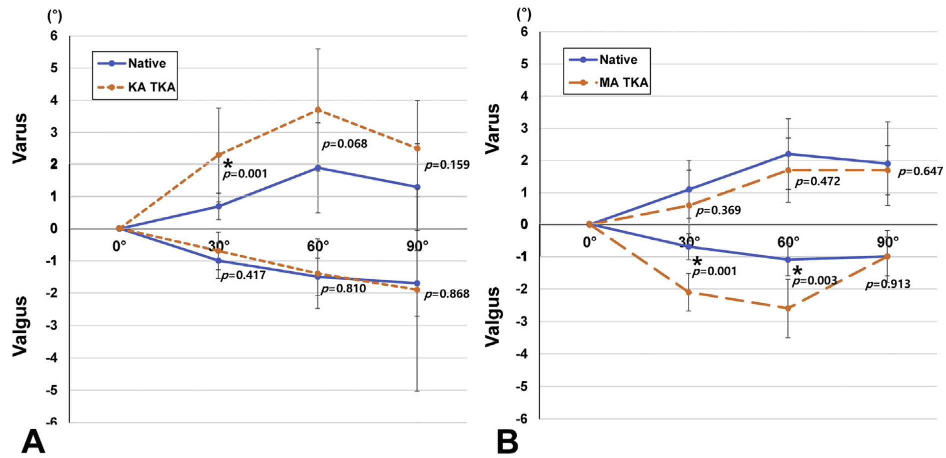

Fig. 4. The patterns of valgus laxity after KA TKA (A) and varus laxity after MA TKA (B) are similar to that of the native knee, but varus laxities after KA TKA and valgus laxities after MA TKA were greater than that of the native knee. Error bars indicate standard deviation. Solid lines indicate the native knees: short dotted lines indicate the knees after KA TKA, and long dotted lines indicate knees after MA TKA. Significant differences ($p < 0.05$) are marked with asterisks.

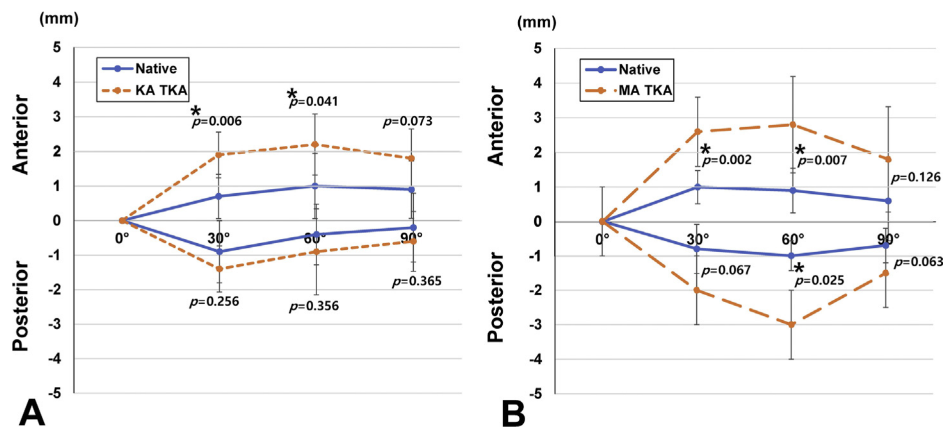

Fig. 5. After both KA (A) and MA (B) TKA, anterior translation increases, but the pattern of posterior translation is similar to that of the native knee. Error bars indicate standard deviation. Solid lines indicate the native knees: short dotted lines indicate the knees after KA TKA, and long dotted lines indicate knees after MA TKA. Significant differences ($p < 0.05$) are marked with asterisks.

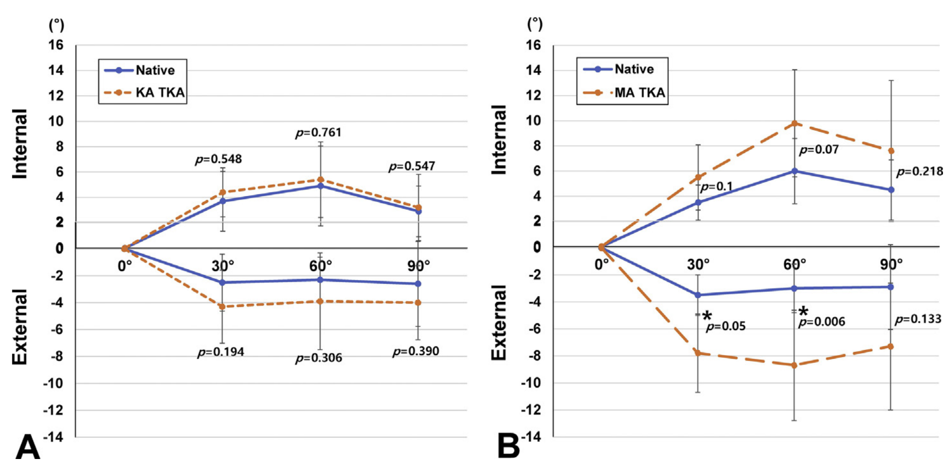

Fig. 6. The patterns of internal and external rotational laxity after KA TKA (A) are similar to those of the native knee. However, after mechanically aligned (MA) TKA (B), external rotation is greater than that of the native knee. Error bars indicate standard deviation. Solid lines indicate the native knees: short dotted lines indicate the knees after KA TKA, and long dotted lines indicate knees after MA TKA. Significant differences ($p < 0.05$) are marked with asterisks.

the more anatomical implant positioning and ligament tension of KA TKA, which allows for a more native joint line and soft tissue laxity and thereby reproduces the medial pivot-motion of the native knee. The results of this study, together with previous studies, indicate that KA TKA may be associated with more physiological functional performance and a more normal knee sensation during activities of daily living than MA TKA [1,2,19,20,41,42].

The results of this study indicate that after KA TKA, the soft tissue laxities are restored closer to that of the native knee than after MA TKA. In this study, the medial and lateral soft tissue laxities throughout the arc of flexion differed between the native and post-TKA knees. In addition, the pattern of most laxities after KA TKA were similar to the native knee, with the exception of varus laxity; whereas after MA TKA, laxities in most directions were increased, especially in the mid-flexion range and only varus laxity was restored. These findings are consistent with several previous studies that reported unequal soft tissue laxities during flexion in the native knee [4], more physiologic soft tissue laxities after KA TKA [5,24,29], and occurrence of mid-flexion instability after MA TKA [9,27]. Of note, this study found that KA TKA reproduced native valgus laxity but MA TKA did not. The reasons why KA TKA restored only valgus laxity whereas MA TKA restored only varus laxity are unclear. One plausible explanation is that the medial and lateral gap are not equal [4,6] and varus laxity is larger than valgus laxity in the native knee [43–45]. These findings, when taken into account with these anatomical circumstances, may be the result of preserving the medial joint space and MCL in KA TKA, whereas the medial and lateral gap were equalized by MCL release in MA TKA. On the other hand, valgus laxity is reported to be a risk factor for paradoxical anterior translation [46] and is associated with poor clinical outcome and dissatisfaction [45]. The results of this study, together with those previous studies, suggest that preservation of medial soft tissue laxity is important to restore physiologic kinematics and provide clues as to why KA TKA improves patient satisfaction. However, neither KA nor MA TKA restored anterior translation. Further biomechanical research investigating the use of a bicruciate retaining/substituting implant or an anterior stabilizing tibial insert following KA TKA is needed to improve the stability of KA TKA.

This study has a number of inherent limitations due to the use of a cadaveric model. First, preparation of each specimen could differ in quality and may not exactly reproduce natural conditions or environments. In addition, the measurement method does not replicate normal gait loads and patterns. Additionally, most specimens were not representative of advanced osteoarthritic knees requiring TKA. These factors should be noted before extrapolating our findings to the in vivo condition. Second, no radiographic examinations were performed and lower limb alignment was not assessed. Thus, no information on preoperative deformity profile and postoperative accuracy were available. In addition, only the knee joint was used and an identical distal femur-cutting angle of 6° valgus was applied to all specimens during TKA. However, all of the specimens were inspected before preparation and they all showed mild varus alignment without severe angular deformity. As 10 cm to 15 cm of the proximal femur and distal tibia were cut from the original specimen until the final length of femur and tibia were 18 cm and 20 cm to the joint line, the initial lengths of the specimens were sufficient to estimate the axes of the femur and tibia. In addition, thicknesses of all resected bone were measured with a caliper and coronal and sagittal thickness measurements were within a clinically acceptable range. Finally, 6° valgus for the distal femur resection is the average difference between the mechanical and anatomical femur axes in a human and is generally acceptable in clinical practice. Nonetheless, the angle between mechanical and anatomical femoral axis can vary [47] and a shortened portion of long bones may be insufficient to determine coronal and sagittal longitudinal axes [48]. Thus, these factors may affect accurate surgical performance and should be considered before interpreting our findings. Third, the TEA was intraoperatively defined by surgeon in this study as the axis connecting the medial epicondylar sulcus with the most prominent aspect of the lateral epicondyle. This method may not be perfectly reproducible but it is the most commonly used method in the clinical practice of experienced knee arthroplasty surgeons. Fourth, we tested only one implant with a single-radius femoral prosthesis and therefore the results are implant-specific. This implant feature must also be considered prior to any broad generalizations. Finally, as our customized knee-testing jig was limited 0 to 90° of knee flexion, we only measured knee kinematics at knee flexion angles $\leq 90^\circ$; hence, biomechanics during deep knee flexion require further study. Despite these limitations, this matched pair cadaveric study appears to provide a valuable biomechanical comparison of knee kinematics and laxity between KA and MA TKA.

5. Conclusions

KA TKA achieves more physiologic kinematics and soft tissue laxity compared to MA TKA. These findings provide clues to understand why KA TKA improves knee functional performance and satisfaction compared to MA TKA and why patients undergoing KA TKA may experience more normal knee sensations.

Disclosure of interest

The authors declare that they have no competing interest.

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Authors' contribution

All authors have made substantive intellectual contributions to this study. I.J.K. and T.Q.L. participated in the design of the study and performed the surgery, I.J.K. wrote the manuscript and performed all surgeries. C.C.L., N.A.P., C.E.C., M.M. and M.H.M. tested and collected data. C.E.C. and S.B.H. reviewed literature, performed statistical analyses and copyedited this manuscript. All authors have read and approved the final manuscript.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.otsr.2019.03.011.

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