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Kinematically aligned total knee arthroplasty reproduces native patellofemoral biomechanics during deep knee flexion

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Abstract

Purpose The implant positioning for kinematically aligned total knee arthroplasty (TKA) differs fundamentally from conventional mechanically aligned TKA. This difference may affect patellofemoral (PF) biomechanics after TKA. This cadaveric study tested the hypothesis that kinematically aligned TKA would restore PF biomechanics to the native condition better than mechanically aligned TKA.

Methods Seven pairs (14 knees) of fresh-frozen cadavers were tested. All specimens were mounted on a customized knee-testing system and digitized using a Microscribe 3DLX instrument (Revware Inc., Raleigh, NC, USA) to measure patellar kinematics in terms of patellar varus/valgus rotation, medial/lateral position, flexion/extension rotation and proximal/distal position at knee flexion angles of 0°, 30°, 60°, 90°, and 120°. The medial and lateral PF joint contact pressure distributions at 120° of knee flexion were measured using a K-scan system (Tekscan Inc., Boston, MA, USA). All patellae remained unresurfaced. For each pair, one knee was randomly assigned to kinematically aligned TKA and the other to mechanically aligned TKA performed using the conventional measured resection technique. During kinematically aligned TKA, the amount of femur and tibia resected was equivalent to implant thickness to maintain the patient-specific joint line. All patellar kinematics were measured and compared between the native condition and after surgery.

Results The patellae of mechanically aligned TKA rotated more valgus and was positioned more laterally compared with those of kinematically aligned TKA at knee flexion angles ≥ 90°. Neither the patellar flexion/extension rotation nor the proximal/distal position differed between either prosthetic knee design and the native knee at all flexion angles. The contact pressure distribution between the medial and lateral PF joint after kinematically aligned TKA were similar to those of the native knee, while the lateral PF joint contact pressure after mechanically aligned TKA was higher than that of the native knee ($p = 0.038$).

Conclusions Kinematically aligned TKA better restores patellar kinematics and PF contact pressure distribution to the native condition than mechanically aligned TKA during deep knee flexion. These findings provide clues to understand why kinematically aligned TKA is associated with less anterior knee pain and better PF functional performance compared to mechanically aligned TKA. Patients undergoing kinematically aligned TKA may experience a more normal feeling during deep knee flexion activities.

Keywords Patellofemoral kinematics · Total knee arthroplasty · Kinematic alignment · Mechanical alignment

Introduction

Advances in implant technology and understanding of knee alignment are fueling the ongoing debate regarding the optimal alignment strategy during total knee arthroplasty (TKA) [1, 7]. Over the past few decades, mechanically aligned (MA) TKA, which seeks neutral alignment and equal mediolateral soft tissue tensions, has been the gold standard of modern TKA. However, during MA TKA, lower limb alignment and soft tissue tension are inevitably altered; thus this systematic strategy may fail to reproduce patient-specific knee alignment and laxity, especially in those with constitutional varus alignment [2, 37]. On the other hand, kinematically aligned (KA) TKA targets restoration of

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Extended author information available on the last page of the article patient-specific, three-dimensional alignment and laxity and thereby reproduces more physiologic kinematics by placing implants that vary by individual anatomy. A growing body of evidence supports that KA TKA reproduces the pre-arthritic anatomy [6, 9, 15, 16, 18] and kinematics [8, 17, 21, 24, 26, 36]. This has led to improved clinical outcomes and a more normal feeling knee [1, 6, 7, 9] with a mid-term implant survivorship similar to MA TKA [13, 14]. Nevertheless, long-term survival and acceptable safe range of implant positioning when performing KA TKA remain unclear. In addition, the biomechanical effect of KA TKA on patellofemoral (PF) joint kinematics is unknown.

Restoration of PF joint biomechanics is important for functional performance after TKA. PF joint biomechanics can be assessed by measuring patellar tracking and contact pressure [20, 34, 35] and these parameters are potentially affected by femoral component design, positioning, and postoperative tibiofemoral kinematics [11, 28–30, 32–34, 38]. In theory, as KA TKA seeks to place a prosthesis in anatomic position, KA TKA may restore pre-arthritic PF joint kinematics by reproducing the constitutional trochlear anatomy and integrity of the patellar ligament. To date, only a few computational simulation studies have reported that the prosthetic trochlear groove after KA TKA better restored the patient-specific groove compared to MA TKA [3, 17, 25, 36]. However, due to between-study heterogeneity in soft tissue conditions and testing jigs, it is difficult to judge the effect of the KA strategy on PF joint biomechanics. Additionally, PF biomechanics after KA TKA may be adversely affected if femoral components designed for MA TKA are used. These include "patella-friendly" concepts such as a laterally oriented trochlear groove with a high lateral flange. Thus, the biomechanical effects of KA TKA on the PF joint remain unclear, and the question of whether KA TKA renders PF kinematics closer to those of the native knee than MA TKA remains unanswered.

The purpose of this study was to quantitatively compare the PF biomechanics between KA and MA TKA in human cadaveric knees. It was hypothesized that KA TKA afforded more physiologic patellar tracking and contact pressure distribution than MA TKA. In addition, this study was conducted to determine whether there are differences in the bone resection thickness following KA and MA TKA. It was also hypothesized that the thickness of bone resection between the two alignment techniques would be different.

Materials and methods

Seven pairs of fresh-frozen knees (14 knees; 5 male pairs and 2 female pairs) with a median age of 67 years (range 58–70 years) were used. All specimens were macroscopically intact and did not exhibit any gross pathology. All subcutaneous tissue was dissected, leaving the extensor mechanism, 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. 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 mounted on a custom knee-testing system, permitting 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). Each eyelet was attached to a cable that passed through pulleys; multiple pulleys afforded reproduction of appropriate in vivo muscle force vectors at each knee flexion angle (Fig. 1) [5, 10, 12]. The ratio of the cross-sectional area-based multiplane loading of the quadriceps and hamstring was used to simulate physiological loading [39].

Patellar kinematics were evaluated at knee flexion angles of 0°, 30°, 60°, 90°, and 120°. A consistent protocol utilizing anatomical landmarks was employed to place three digitizing markers on each patella, femur, and tibia. Kinematic data were collected using a Microscribe 3DLX 3

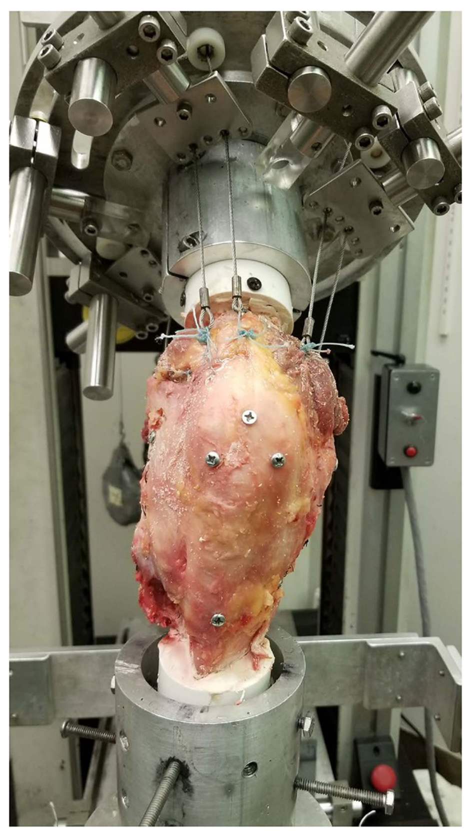

Fig. 1 Custom knee testing system with six degrees-of-freedom

dimensional digitizing instrument (Revware Inc., Raleigh, NC, USA). Each measurement was performed in duplicate and the data averaged. Repeatability was checked; a third trial was performed if the difference between the first two trials was > 1 mm or > 1°. PF kinematics were assessed by measuring patellar varus/valgus rotation, medial/lateral position, flexion/extension rotation, and proximal/distal position. The varus/valgus rotation was defined as rotation in the transverse plane about the superior/inferior axis of the patella, the medial/lateral position was the distance from the middle of the patella to those of the trochlear groove, the flexion/extension rotation was the rotation of the patella in the sagittal plane about the transepicondylar axis (TEA), and the proximal/distal position was the distal movement of the patella on the trochlea [27]. PF contact pressure was assessed by measuring medial and lateral PF joint contact areas and pressures at a knee flexion angle of 120°, using the K-scan system (Tekscan Inc., South Boston, MA, USA). A 2-point calibration was performed for loads of 15 and 100 N and the saturation pressure was determined to be 1369 kPa based on this calibration. The K-scan sensor (Model 4000) was inserted through the suprapatellar pouch.

For each cadaver, one knee was randomly assigned to the KA TKA and the other to the MA TKA group. All specimens were evaluated pre- and postoperatively. All surgical procedures were performed by a single senior surgeon (K.I.J.) using a standard cruciate-retaining prosthesis instrumentation system (Lospa; Corentec Co. Ltd., Seoul, Korea) with high conformity tibial insert design. The thickness of distal and posterior femur implant was 9 mm and 10 mm, respectively. After performing subvastus arthrotomy, the deep medial collateral ligament was released. All patellae remained unresurfaced. In the MA TKA group, TKA was performed using the conventional measured resection technique. Resection of the distal femur was performed at a 6° valgus angle and the TEA was used as a reference. Proximal tibial resection was performed to resect a 10 mm-thick portion of the lateral plateau at a cutting angle 90° to the tibial axis. Finally, measurement of the full extension and 90° flexion gaps was performed using a tensor device. Multiple needle puncture (MNP) with a standard 18-gauge aspiration needle was performed in the most tense fibers of the medial soft tissue if necessary [19]. MNP was performed in four of the seven knees (57%). KA TKA was performed as previously described [15, 23]. 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 [23]. 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 of the distal and posterior femur and tibia differed substantially (Table 1). This cadaveric study was exempted from the institutional review board of VA Long Beach Healthcare System because it did not involve human subjects.

Statistical analysis

All data are presented as medians with ranges. All values at each tested flexion angle were converted into differences from the value at full extension; these corrected values were then compared. The differences in all the dependent variables between the prosthetic knee and the native knee treated with either MA or KA within a pair were computed. For the MA and KA methods, the differences between the prosthetic and native knee dependent variables at each flexion angle were compared using a two-factor ANOVA. The Mann–Whitney *U* test was employed to compare the resected bone thicknesses between MA and KA TKA knees, and all differences between prosthetic and native knees. All computations were performed using SPSS for Windows software (ver. 21.0; IBM Corp., Armonk, NY, USA); a p value < 0.05 was taken to indicate statistical significance.

A priori power analysis based on the results of previous biomechanical studies regarding changes of PF joint biomechanics after TKA was performed to determine the necessary sample size needed for sufficient statistical power [11, 33]. Using the two-sided hypothesis test at an alpha level of 0.05 and a power of 80%, it was found that seven knees in each group were required to detect a 2° difference in varus/valgus rotation and a 1-mm difference in medial/lateral position, and 40% difference of contact pressure. These values were considered biomechanically meaningful because they

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

	KA TKA	MA TKA	*p* value
Distal femur			
Medial	9.7 (9.2, 10.2)	11.0 (9.0, 11.5)	0.005
Lateral	10.0 (9.5, 10.8)	7.0 (6.2, 8.0)	< 0.001
Posterior femur			
Medial	11.0 (10.0, 12.0)	13.0 (11.0, 15.1)	0.007
Lateral	12.0 (11.0, 12.0)	10.0 (7.0, 11.0)	0.003
Tibia			
Medial	8.0 (7.0, 9.0)	2.0 (1.4, 2.3)	< 0.001
Lateral	8.5 (8.0, 9.0)	10.0 (8.5, 10.2)	0.002

Data are presented as medians (range)

KA kinematically aligned, *MA* mechanically aligned, *TKA* total knee arthroplasty were reported as the mean differences between the native and prosthetic knee in human cadaveric tests.

Results

KA TKA achieved greater restoration of patellar tracking to the native knee during deep knee flexion compared to MA TKA. The patellae following MA TKA were rotated more valgus than those of KA TKA at knee flexion angles of 90° and 120°. The amount of patellar varus/valgus rotation differences between prosthetic knee and native knee following MA TKA were larger than those of KA TKA at knee flexion angles of 90° and 120° (Fig. 2). In addition, patellae following MA TKA were positioned more laterally than those of KA TKA at knee flexion angles of 90° and 120° (Fig. 3). However, the patellar flexion/extension rotation (Fig. 4) and proximal/distal position (Fig. 5) after both KA TKA and MA TKA were similar to those of the native knee at all flexion angles.

KA TKA afforded greater restoration of PF joint contact pressure distribution to the native knee during deep knee flexion. The contact areas of the medial and lateral PF joints at 120° of flexion decreased after either operation, but differences between prosthetic and native knee were similar, regardless of the alignment strategy used (Fig. 6). On the other hand, the contact pressure difference of the medial PF joint between prosthetic and native knee following MA TKA was similar to those of KA TKA (Fig. 7.). However, in the lateral PF joint, the contact pressure difference between prosthetic and native knee following MA TKA was significantly higher than those of KA TKA (Fig. 8).

The pattern of resected bone thickness after KA TKA significantly differed from those of MA TKA (Table 1). After KA TKA, the resected bone thickness of femur and tibia on the medial side was similar to those of the lateral side and were equivalent to implant thickness. On the other hand, following MA TKA, the resected bone thickness of the femur on the medial side was thicker than the lateral side while the resected bone thickness of the tibia on the lateral side was thicker than the medial side. Thus, the native joint line was preserved following KA TKA, whereas the joint line was made perpendicular to the mechanical axis following MA TKA.

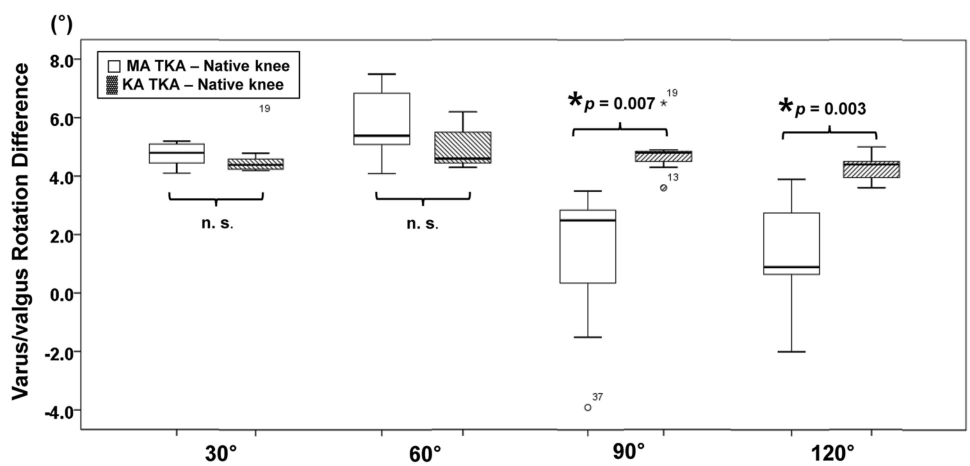

Fig. 2 Prosthetic and native knee varus/valgus rotation differences from full extension comparing mechanically aligned (MA) and kinematically aligned (KA) TKA for 30, 60, 90 and 120° knee flexion angle (varus +/valgus –). Significant differences ($p < 0.05$) are marked with asterisks. *n.s.* not significant

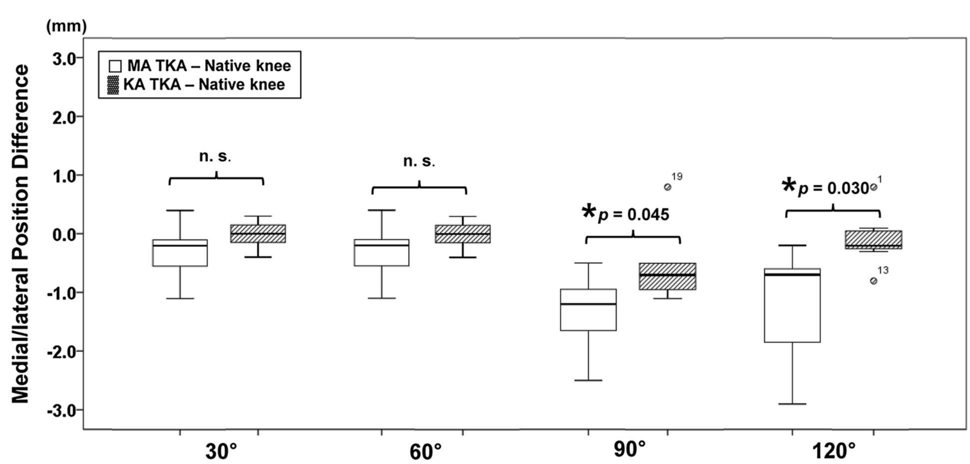

Fig. 3 Prosthetic and native knee medial/lateral position differences from full extension comparing MA and KA TKA for 30, 60, 90 and 120° knee flexion angle (medial +/lateral –). Significant differences ($p < 0.05$) are marked with asterisks. *n.s.* not significant

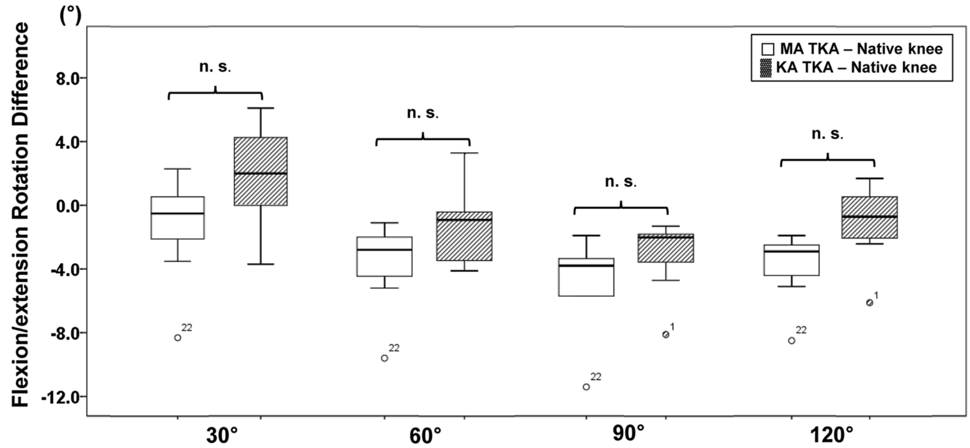

Fig. 4 Prosthetic and native knee flexion/extension rotation differences from full extension comparing MA and KA TKA for 30, 60, 90 and 120° knee flexion angle (flexion +/extension –). *n.s.* not significant

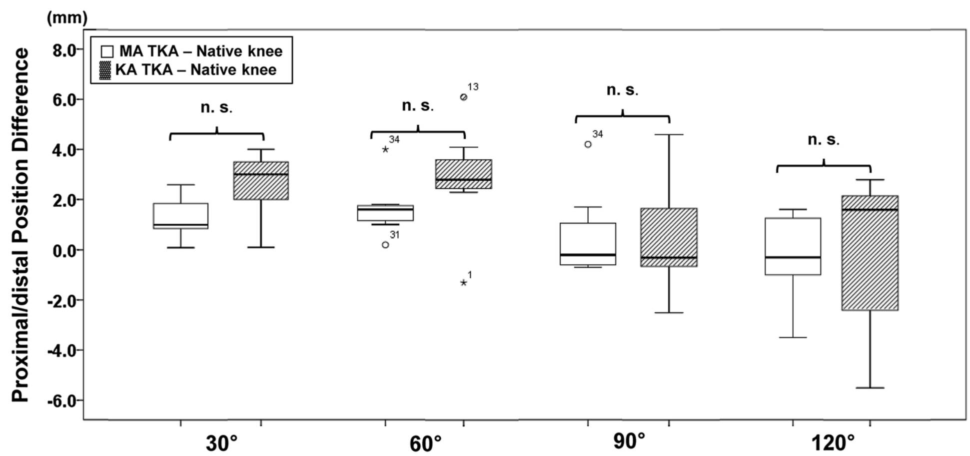

Fig. 5 Prosthetic and native knee proximal/distal position differences from full extension comparing MA and KA TKA for 30, 60, 90 and 120° knee flexion angle (proximal +/distal –). *n.s.* not significant

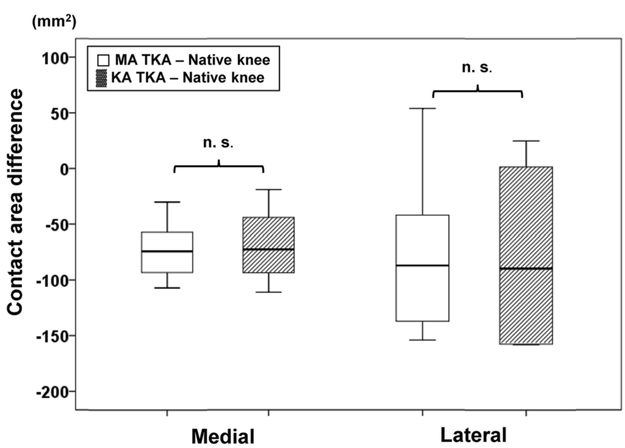

Fig. 6 Differences from native knee contact area comparing MA and KA TKA in the medial and lateral patellofemoral (PF) joints at 120° of flexion. *n.s.* not significant

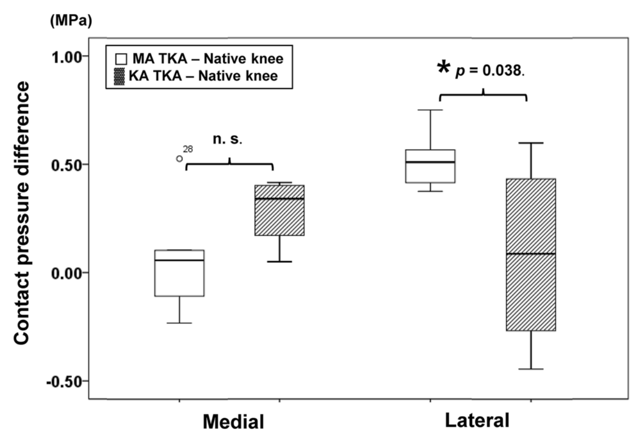

Fig. 7 Differences from native knee contact pressures comparing MA and KA TKA in the medial and lateral PF joints at 120° of flexion. Significant differences ($p < 0.05$) are marked with asterisks. *n.s.* not-significant

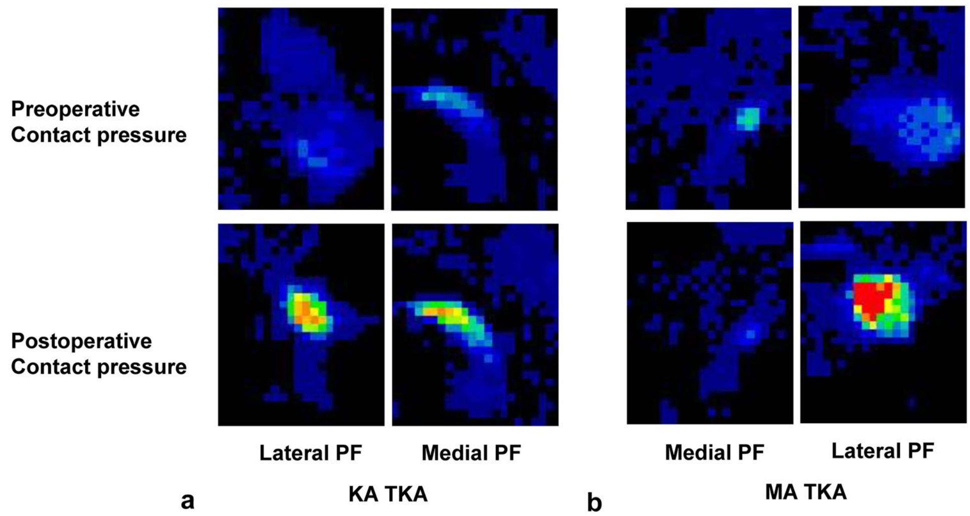

Fig. 8 Representative Tekscan images of medial and lateral PF joint contact distributions pattern following KA TKA (**a**) and MA TKA (**b**)

Discussion

The most important finding of this study was that KA TKA reproduced patellar tracking and PF joint contact pressure distribution during deep flexion more physiologically than MA TKA. As both prosthetic trochlear morphology and tibiofemoral kinematics affect PF joint biomechanics after TKA [11, 29, 30, 32, 33, 38], PF kinematics after KA TKA would be expected to differ from those after MA TKA. However, while PF complication rates after KA and MA TKA are similar; a problematic PF joint is the most common cause of revision following KA TKA [7, 9]. In addition, the lack of PF kinematic data after KA TKA renders it difficult to evaluate the reproducibility of PF kinematics following KA TKA.

This study demonstrated that KA TKA afforded patellar tracking more similar to the native state than MA TKA during deep flexion. In this study, patellar varus/valgus rotation and medial/lateral position after KA TKA were similar to those of the native knee at all flexion angles, but those after MA TKA were rotated more valgus and positioned more laterally than the native knee at flexion angles of 90° and 120°. It is difficult to compare this study with previous studies because of substantial variations in study design, methodology, and assumptions [17, 36]. However, the results of this study are similar to previous studies reporting patellar varus/valgus rotation and medial/lateral position changes after TKA [11, 27, 33–35] and agree with prior conclusions that KA TKA restored more native PF kinematics in deeper flexion than MA TKA [17, 25, 36]. This may reflect the more anatomical implant positioning during KA TKA, which allows for more physiological PF kinematics as the native joint line was preserved following KA TKA. In addition, these findings suggested that PF functional performance after KA TKA may be enhanced, especially during deep flexion activities.

Recently, there is emerging concern about the necessity of designing a femoral component with a trochlea shaped specifically for KA TKA [3, 25]. Most current implants are designed for use in MA TKA and incorporate "patella-friendly" concepts such as a laterally oriented trochlear groove with a high lateral flange. As the femoral component of KA TKA is usually internally rotated and placed more valgus than that of MA TKA, the prosthetic trochlear groove following KA TKA is less valgus, more internally rotated and more medially located than that of MA TKA [25]. Hence, such design concepts may increase the risk of patellar instability during early flexion, as a flexed femoral component is a risk factor for patellar mal-tracking following KA TKA [3, 17, 22]. However, data from this current study showed that all PF kinematic parameters during early flexion were similar to the native knee, regardless of the alignment strategy. These findings are in agreement with the results of previous studies reporting similar mid-term PF complication rates of KA and MA TKA [6, 9, 14, 22]. The results of this study, together with those of previous studies, suggest that the sources of patellar mal-tracking are multifactorial with tibiofemoral kinematics playing an important role. Further research on optimal prosthetic trochlear morphology and patellar tracking reflecting tibiofemoral kinematics following KA TKA are needed.

The present study's findings support the hypothesis that the contact pressure distribution after KA TKA would be restored closer to that of the native knee than after MA TKA. The contact areas at deep knee flexion were less than those of the native knee, regardless of the alignment strategy employed. However, the contacts of the medial and lateral PF joint pressures in deep knee flexion following KA TKA were evenly distributed and were similar to the native knee,; whereas after MA TKA, only the lateral PF joint contact pressure increased. Previous studies observed similar increases of contact pressure in the lateral PF joint after TKA when comparing MA TKA to native knees [11, 31]. However, as there are no previous studies evaluating the

PF contact pressure of un-resurfaced patella after KA TKA, these results of KA TKA are difficult to compare with other studies. The PF contact pressure distribution after TKA is directly affected by PF kinematics and contact area and also by potentially altered femoral rollback motion [30]. The results of this study may be attributable to more physiologic trochlear morphology and PF kinematics [17, 25, 36] and femoral rollback following KA TKA than after MA TKA [17, 21, 24, 26, 36]. Meanwhile, higher PF contact pressure and altered patellar tracking may cause anterior knee pain [4, 11]. These findings illustrated that KA TKA may be associated with a more normal knee sensation and less anterior knee pain than MA TKA [1, 6, 7, 9].

This study had certain limitations. First, no preoperative radiographic examinations were performed and no intraoperative computer-assisted system was used; therefore, lower limb alignment was not assessed. This may affect precise preoperative planning and surgical procedure accuracy. However, the caliper measurement technique with generic instrument system was reported to restore preoperative limb alignment, distal lateral femoral angle, and proximal medial tibial angle when performing KA TKA [15, 23]. Second, in an effort to avoid possible confounders of PF kinematics, no patellar resurfacing was performed, so our findings should be generalized with caution. Third, we tested only one implant (a recently approved, single-radius femoral prosthesis featuring a deep, elongate trochlear groove with a lateral tilt and a high lateral flange). As femoral component design affects PF kinematics, this constraint must also be considered prior to any broad generalization. Fourth, contact pressure distribution was measured at a knee flexion angle of 120° to simulate squatting (when PF contact stress is maximal). Contact distribution during early flexion requires further study. Fifth, as this study focused largely on the PF joint, we did not explore whether tibiofemoral kinematics after KA TKA affected PF biomechanics. However, several previous studies found that KA TKA afforded better femoral rollback than MA TKA [17, 21, 24, 26]. Sixth, we did not take into account the effect of changes of the Q angle, which might be a major factor affecting PF joint biomechanics. Finally, as 14 knees were tested in this study, it is possible that the study was underpowered and subject to type II error. Despite these limitations, this cadaveric study is believed to provide valuable biomechanical comparison of PF kinematics and contact distribution between KA and MA TKA.

Conclusion

KA TKA reproduces more physiologic patellar tracking and PF contact pressure distribution during deep knee flexion than MA TKA. These findings provide clues to understand why KA TKA improves PF functional performance compared to MA TKA and why patients undergoing KA TKA experience better patellar tracking and less anterior knee pain.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding authors identify the following possible conflict of interest: Corentec Co. Ltd. donated all prostheses used in this study. The company had no input into the study design, or data collection or interpretation. The company was not involved in manuscript preparation or the decision to submit the article to this journal.

Ethical approval This article does not contain any studies with human participants performed by any of the authors.

Informed consent For this type of study formal consent is not required.

References

1. Abdel MP, Oussedik S, Parratte S, Lustig S, Haddad FS (2014) Coronal alignment in total knee replacement: historical review, contemporary analysis, and future direction. Bone Jt J 96-b(7):857–862
2. Bellemans J, Colyn W, Vandenneucker H, Victor J (2012) The Chitranjan Ranawat award: is neutral mechanical alignment normal for all patients? The concept of constitutional varus. Clin Orthop Relat Res 470(1):45–53
3. Brar AS, Howell SM, Hull ML, Mahfouz MR (2016) Does kinematic alignment and flexion of a femoral component designed for mechanical alignment reduce the proximal and lateral reach of the trochlea? J Arthroplasty 31(8):1808–1813
4. Breugem SJ, van Ooij B, Haverkamp D, Sierevelt IN, van Dijk CN (2014) No difference in anterior knee pain between a fixed and a mobile posterior stabilized total knee arthroplasty after 7.9 years. Knee Surg Sports Traumatol Arthrosc 22(3):509–516
5. Bryant BJ, Tilan JU, McGarry MH, Takenaka N, Kim WC, Lee TQ (2014) The biomechanical effect of increased valgus on total knee arthroplasty: a cadaveric study. J Arthroplasty 29(4):722–726
6. Calliess T, Bauer K, Stukenborg-Colsman C, Windhagen H, Budde S, Ettinger M (2017) PSI kinematic versus non-PSI mechanical alignment in total knee arthroplasty: a prospective, randomized study. Knee Surg Sports Traumatol Arthrosc 25(6):1743–1748
7. Courtney PM, Lee GC (2017) Early outcomes of kinematic alignment in primary total knee arthroplasty: a meta-analysis of the literature. J Arthroplasty 32(6):2028–2032
8. Delport H, Labey L, Innocenti B, De Corte R, Vander Sloten J, Bellemans J (2015) Restoration of constitutional alignment in TKA leads to more physiological strains in the collateral ligaments. Knee Surg Sports Traumatol Arthrosc 23(8):2159–2169

9. Dossett HG, Estrada NA, Swartz GJ, LeFevre GW, Kwasman BG (2014) A randomised controlled trial of kinematically and mechanically aligned total knee replacements: two-year clinical results. Bone Jt J 96-b(7):907–913
10. Fornalski S, McGarry MH, Bui CN, Kim WC, Lee TQ (2012) Biomechanical effects of joint line elevation in total knee arthroplasty. Clin Biomech (Bristol Avon) 27(8):824–829
11. Glogaza A, Schroder C, Woiczinski M, Muller P, Jansson V, Steinbruck A (2018) Medial stabilized and posterior stabilized TKA affect patellofemoral kinematics and retropatellar pressure distribution differently. Knee Surg Sports Traumatol Arthrosc 26(6):1743–1750
12. Hofer JK, Gejo R, McGarry MH, Lee TQ (2012) Effects of kneeling on tibiofemoral contact pressure and area in posterior cruciate-retaining and posterior cruciate-sacrificing total knee arthroplasty. J Arthroplasty 27(4):620–624
13. Howell SM, Howell SJ, Kuznik KT, Cohen J, Hull ML (2013) Does a kinematically aligned total knee arthroplasty restore function without failure regardless of alignment category? Clin Orthop Relat Res 471(3):1000–1007
14. Howell SM, Papadopoulos S, Kuznik K, Ghaly LR, Hull ML (2015) Does varus alignment adversely affect implant survival and function six years after kinematically aligned total knee arthroplasty? Int Orthop 39(11):2117–2124
15. Howell SM, Papadopoulos S, Kuznik KT, Hull ML (2013) Accurate alignment and high function after kinematically aligned TKA performed with generic instruments. Knee Surg Sports Traumatol Arthrosc 21(10):2271–2280
16. Hutt J, Masse V, Lavigne M, Vendittoli PA (2016) Functional joint line obliquity after kinematic total knee arthroplasty. Int Orthop 40(1):29–34
17. Ishikawa M, Kuriyama S, Ito H, Furu M, Nakamura S, Matsuda S (2015) Kinematic alignment produces near-normal knee motion but increases contact stress after total knee arthroplasty: a case study on a single implant design. Knee 22(3):206–212
18. Ji HM, Han J, Jin DS, Seo H, Won YY (2016) Kinematically aligned TKA can align knee joint line to horizontal. Knee Surg Sports Traumatol Arthrosc 24(8):2436–2441
19. Koh IJ, Kwak DS, Kim TK, Park IJ, In Y (2014) How effective is multiple needle puncturing for medial soft tissue balancing during total knee arthroplasty? A cadaveric study. J Arthroplasty 29(12):2478–2483
20. Leichtle UG, Wunschel M, Leichtle CI, Muller O, Kohler P, Wulker N et al (2014) Increased patellofemoral pressure after TKA: an in vitro study. Knee Surg Sports Traumatol Arthrosc 22(3):500–508
21. Nakamura S, Tian Y, Tanaka Y, Kuriyama S, Ito H, Furu M et al (2017) The effects of kinematically aligned total knee arthroplasty on stress at the medial tibia: a case study for varus knee. Bone Jt Res 6(1):43–51
22. Nedopil AJ, Howell SM, Hull ML (2017) What clinical characteristics and radiographic parameters are associated with patellofemoral instability after kinematically aligned total knee arthroplasty? Int Orthop 41(2):283–291
23. Nedopil AJ, Singh AK, Howell SM, Hull ML (2018) Does calipered kinematically aligned TKA restore native left to right symmetry of the lower limb and improve function? J Arthroplasty 33(2):398–406
24. Riley J, Roth JD, Howell SM, Hull ML (2018) Internal-external malalignment of the femoral component in kinematically aligned total knee arthroplasty increases tibial force imbalance but does not change laxities of the tibiofemoral joint. Knee Surg Sports Traumatol Arthrosc 26(6):1618–1628
25. Riviere C, Iranpour F, Harris S, Auvinet E, Aframian A, Parratte S et al (2018) Differences in trochlear parameters between native and prosthetic kinematically or mechanically aligned knees. Orthop Traumatol Surg Res 104(2):165–170
26. Roth JD, Howell SM, Hull ML (2018) Kinematically aligned total knee arthroplasty limits high tibial forces, differences in tibial forces between compartments, and abnormal tibial contact kinematics during passive flexion. Knee Surg Sports Traumatol Arthrosc 26(6):1589–1601
27. Sharma A, Grieco TF, Zingde SM, Dennis DA, Anderle MR, Komistek RD (2017) In vivo three-dimensional patellar mechanics: normal knees compared with domed and anatomic patellar components. J Bone Jt Surg Am 99(5):e18
28. Slevin O, Schmid FA, Schiapparelli F, Rasch H, Hirschmann MT (2018) Increased in vivo patellofemoral loading after total knee arthroplasty in resurfaced patellae. Knee Surg Sports Traumatol Arthrosc 26(6):1805–1810
29. Slevin O, Schmid FA, Schiapparelli FF, Rasch H, Amsler F, Hirschmann MT (2017) Coronal femoral TKA position significantly influences in vivo patellar loading in unresurfaced patellae after primary total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 25(11):3605–3610
30. Steinbruck A, Fottner A, Schroder C, Woiczinski M, Schmitt-Sody M, Muller T et al (2017) Influence of mediolateral tibial baseplate position in TKA on knee kinematics and retropatellar pressure. Knee Surg Sports Traumatol Arthrosc 25(8):2602–2608
31. Steinbruck A, Schroder C, Woiczinski M, Fottner A, Muller PE, Jansson V (2013) Patellofemoral contact patterns before and after total knee arthroplasty: an in vitro measurement. Biomed Eng Online 12:58
32. Steinbruck A, Schroder C, Woiczinski M, Muller T, Muller PE, Jansson V et al (2016) Influence of tibial rotation in total knee arthroplasty on knee kinematics and retropatellar pressure: an in vitro study. Knee Surg Sports Traumatol Arthrosc 24(8):2395–2401
33. Steinbruck A, Schroder C, Woiczinski M, Schmidutz F, Muller PE, Jansson V et al (2017) Mediolateral femoral component position in TKA significantly alters patella shift and femoral roll-back. Knee Surg Sports Traumatol Arthrosc 25(11):3561–3568
34. Stoddard JE, Deehan DJ, Bull AM, McCaskie AW, Amis AA (2014) No difference in patellar tracking between symmetrical and asymmetrical femoral component designs in TKA. Knee Surg Sports Traumatol Arthrosc 22(3):534–542
35. Tanikawa H, Tada M, Harato K, Okuma K, Nagura T (2017) Influence of total knee arthroplasty on patellar kinematics and patellofemoral pressure. J Arthroplasty 32(1):280–285
36. Theodore W, Twiggs J, Kolos E, Roe J, Fritsch B, Dickison D et al (2017) Variability in static alignment and kinematics for kinematically aligned TKA. Knee 24(4):733–744
37. Vandekerckhove PTK, Matlovich N, Teeter MG, MacDonald SJ, Howard JL, Lanting BA (2017) The relationship between constitutional alignment and varus osteoarthritis of the knee. Knee Surg Sports Traumatol Arthrosc 25(9):2873–2879
38. Werth L, Saffarini M, Amsler F, Abdelkafy A, Hirschmann MT (2017) The need for secondary resurfacing is affected by trochlear height in total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc 25(12):3818–3823
39. Wickiewicz TL, Roy RR, Powell PL, Edgerton VR (1983) Muscle architecture of the human lower limb. Clin Orthop Relat Res (179):275–283

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