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KNEE

Kinematically aligned TKA restores physiological patellofemoral biomechanics in the sagittal plane during a deep knee bend

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Abstract

Purpose Although patellofemoral complications after kinematically aligned (KA) TKA are infrequent, the patellar flexion angle and proximal–distal patellar contact location through flexion, and incidence of patellar loss of contact at full extension are unknown. The present study determined whether the patellar flexion angle and proximal–distal patellar contact location of a KA TKA performed with anatomic, fixed-bearing, posterior cruciate-retaining (PCR) components differed from those of the native contralateral knee during a deep knee bend, and determined the incidence of patellar loss of contact at full extension for KA TKA only.

Methods During a deep knee bend from full extension to maximum flexion, both knees were imaged in a lateral view using single-plane fluoroscopy for 25 patients with a calipered KA TKA and a healthy native knee in the contralateral limb. The patellar flexion angle and proximal–distal patellar contact location were measured on images from full extension to maximum flexion in 30° increments. Paired *t* tests at each flexion angle determined the significance of the difference between the KA TKA knees and the native contralateral knees. In the KA TKA knees, the incidence of patellar loss of contact at full extension was determined. Patient-reported outcome scores also were recorded including the Oxford Knee Score.

Results Mean patellar flexion angles were not different between the KA TKA knees and the native contralateral knees throughout the motion arc. The largest statistically significant difference in the mean proximal–distal patellar contact locations was 4 mm. The incidence of patellar loss of contact in the KA TKA knees at full extension was 8% (2 of 25 patients). The median Oxford Knee Score was 46 out of 48.

Conclusions Calipered KA TKA performed with anatomic, fixed-bearing, PCR components restored patellar flexion angles to native and largely restored the proximal–distal patellar contact locations, which at most differed from the native contralateral knee by approximately 10% of the mean proximal–distal patellar length. In the KA TKA knees, the incidence of patellar loss of contact was infrequent. These objective biomechanical results are consistent with the relatively high subjective patient-reported outcome scores herein and support the low incidence of patellofemoral complications following KA TKA previously reported.

Level of evidence Therapeutic, level III.

Keywords Total knee replacement · Total knee arthroplasty · Prosthetic knee · Patellar kinematics · Patellar contact · Patellar loss of contact · Normal daily activities · Single plane fluoroscopy

Introduction

Patellofemoral joint complications following total knee arthroplasty (TKA) include anterior knee pain, subluxation, and extensor mechanism deficiency and represent some of the primary sources of patient dissatisfaction and non-infectious indications of revision surgery [30, 36]. These complications can often be attributed to malalignment of the femoral, tibial, and/or patellar components [2, 26]. Accordingly, designing and surgically aligning

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TKA components to restore patellofemoral joint function to that of the native, healthy knee might prevent these complications.

With the intent of restoring function of the prosthetic knee to that of the native healthy knee without ligament release, kinematically aligned (KA) TKA was conceived [12]. KA TKA is a viable alternative to mechanically aligned (MA) TKA because short-term patient-reported outcomes are comparable to [40, 41] or better than [4, 6, 22, 24] those of MA TKA. Moreover in the long term, implant survivorship is high (98.4% for aseptic failure) and high function is maintained (mean Oxford Knee Score = 43) [14]. Kinematic alignment strives to restore the joint lines of the native (i.e. pre-arthritic) knee without placing restrictions on the preoperative deformity and postoperative correction, and without ligament releases. Because KA TKA strives to restore the joint lines of the native knee by adjusting resection thickness to compensate for cartilage wear and bone loss [27] and because KA TKA better restores the native trochlear morphology than MA TKA [21], patellofemoral joint function might be restored to that of the native knee as well.

Several biomechanical variables provide objective measures of patellofemoral joint function following TKA. Patellar flexion angles and proximal–distal patellar contact locations describe the rotation of the patella relative to the femur and location of contact on the patella by the femur, respectively, in the sagittal plane during flexion activities [17, 20]. Patellar loss of contact at full extension is another objective measure [20]. Therefore, surgical alignment methods together with implant designs used with such methods should be evaluated for differences in patellar flexion angle and proximal–distal patellar contact location from the native knee, and also patellar loss of contact at full extension. Although patellofemoral complications after KA TKA are infrequent [14, 26], whether patellofemoral joint function is restored to native following KA TKA is unknown.

Accordingly, the present study determined whether the patellar flexion angle and proximal–distal patellar contact location of a KA TKA performed with anatomic, fixed-bearing, posterior cruciate-retaining (PCR) components differed from those of the native contralateral knee during a deep knee bend and determined the incidence of patellar loss of contact at full extension for a KA TKA only. This study also reported the overall patient function at a minimum follow up of 14 months as measured by the Oxford Knee, Knee Society, Forgotten Joint, WOMAC, and UCLA scores. Our hypothesis was that the biomechanical variables would not differ from those of native knee. If this hypothesis was accepted, then this would provide an objective biomechanical explanation for the previously reported clinical findings that the incidence of patellofemoral complications is low following KA TKA [14, 26].

Methods

Patients

This study was approved by the Institutional Review Board at the University of California, Davis (IRB# 954288). Inclusion criteria were patients having an anatomic, fixed-bearing, PCR KA TKA (Persona CR, Zimmer-Biomet, Warsaw, IN) and native contralateral limb with no skeletal abnormalities or prior surgery in either limb except for the KA TKA, no history of rheumatic or traumatic arthritis, age between 40 and 85 years, a body mass index less than or equal to 40, ability to perform activities of daily living without discomfort in the native contralateral limb, and ability to have an MR scan of the native contralateral limb. Note that patients were selected with no restriction on preoperative varus–valgus or flexion-contracture deformity. Between November 2014 and April 2017, one surgeon performed calipered KA TKA on 1201 consecutive patients. A review of post-operative CT scans and medical records for these patients revealed that 93 met the inclusion criteria. Patients meeting the inclusion criteria were contacted at random until 31 agreed to participate and gave informed consent. Of those who gave informed consent, two were excluded due to the presence of osteoarthritis on MRI or standing AP fluoroscopic image, one was excluded due to lost data on the fluoroscope, two were excluded due to having a different implant design, and the pilot patient was excluded due to technical problems, which left 14 males and 11 females that participated in the study (Table 1).

Surgical technique

Using ten sequential caliper measurements and a series of verification checks with manual instruments, KA TKA was performed by a single surgeon using a midvastus approach following a previously described technique [27]. Anatomic, fixed-bearing, PCR components and a patella button were implanted with cement (Persona CR, Zimmer-Biomet, Warsaw, IN). For the femoral component, the varus–valgus orientation and proximal–distal location were set to restore the native distal femoral joint line by adjusting the thickness of the distal femoral resections as measured with a caliper to within 0 ± 0.5 mm of the thickness of the femoral component condyles after compensating for cartilage wear and saw blade kerf. The internal–external orientation and anterior–posterior location were set to restore the native posterior joint line by adjusting the thickness of the posterior femoral resections as for the distal femoral joint line. These steps set the femoral

Table 1 Demographic patient data and patient-reported outcome scores at the time of imaging

$N=25$	
Demographic patient data	Mean ± standard deviation (range)
Age (years)	64 ± 7 (52–82)
Sex	14 males, 11 females
BMI (kg/m^2)	29 ± 5 (22–40)
Preoperative weight bearing varus (+)/valgus (−) deformity (°)	0.1 ± 8.2 (13 to − 15)
Passive extension, KA TKA (°)	0 ± 1 (0–5)
Passive flexion, KA TKA (°)	118 ± 12 (95–140)
Passive extension, native (°)	0 ± 0 (0–0)
Passive flexion, native (°)	128 ± 8 (105–140)
Follow-up time (months)	28 ± 8 (14–42)
Patient-reported outcomes	Median (range)
Oxford Knee Score (48 best, 0 worst)	46 (28–48)
WOMAC Score (0 best, 96 worst)	3 (0–43)
Forgotten Joint Score (100 best, 0 worst)	75 (2–100)
Knee Society Score (150 best, − 20 worst)	140 (80–150)
UCLA Score (10 best, 1 worst)	7 (5–10)

component with a bias of 0.3° and precision of ± 1.1° with respect to the flexion–extension plane of the knee [25].

For the tibial component, the varus–valgus orientation was set to restore the native joint line by ensuring that the thicknesses measured with a caliper at the base of the tibial spines medially and laterally were within 0 ± 0.5 mm of each other. With the knee in full extension, the varus–valgus angle of the tibial resection was fine-tuned working in 1°–2° increments until the varus–valgus laxity was negligible as in the native knee [33]. The internal–external orientation of the tibial component was set using a kinematic tibial template with a negligible bias of 0.1° external and a precision of ± 3.9° [28]. With the knee in 90° of flexion, the slope was set to restore the native joint line in the medial compartment by working in 1°–2° increments until the offset of the anterior tibia from the distal medial femoral condyle with trial components matched that of the knee at exposure after adjusting for cartilage wear on the femur and ensuring that the internal–external laxity approximated 14° as in the native knee [33]. Ligament releases were not performed. This surgical procedure restores the hip–knee–ankle angle, distal lateral femoral angle, and proximal medial tibial angle to native within ± 3° with frequencies of 95%, 97%, and 97%, respectively [27].

Data collection

During a deep knee bend from full extension to maximum flexion, fluoroscopic images (OEC 9900 Elite, General Electric, Boston, MA) were recorded for each patient's native contralateral and KA TKA knees at 15 frames per second. During all imaging, a 25.4 mm diameter steel sphere was situated behind the knee and held in place with an elastic wrap. To establish the fluoroscope settings, all noise reduction functions on the fluoroscope were disabled. Next, the patient's knee under study was statically imaged with the automatic brightness and contrast setting enabled on the fluoroscope to adjust the imaging parameters specific to the patient's anatomy. When the image was deemed suitable in terms of brightness and contrast, these parameters were fixed for the dynamic recording. Patients were instructed to stagger their stance in the AP direction to prevent the contralateral knee from impeding the view of the knee under study, and to keep both feet planted on the platform. When the patient's initial position was set with the knee in full extension, a scout image was taken and the orientation of the imaging plane was iteratively adjusted until the patient's posterior femoral condyles were superimposed, thereby defining a lateral view. Patients were then instructed to perform the activity over 5–7 s to reduce motion blur. Hand rails were provided to aid in stability.

With the patient lying supine, an orthopaedic surgery resident measured the passive limits of extension and flexion in each knee (Table 1). The knee was taken to the full extent of extension until a firm endpoint was encountered, and this degree of flexion was visually estimated and recorded. Allowing the hip to flex, the knee was taken to the full extent of flexion until a firm endpoint was encountered, and this degree of flexion was visually estimated and recorded [29].

Patient-reported outcome scores were obtained at the time of imaging at a mean of 28 months after surgery (Table 1).

Data processing

Fluoroscopic images were corrected for distortion after which images at 0°, 30°, 60°, 90°, and maximum flexion were identified and subsequently imported into another custom script in Matlab (Mathworks, Natick, MA) to compute the patellar flexion angle, proximal–distal patellar contact location, and the patellar separation distance at full extension in the KA TKA knee. First, at least 20 points were digitized in approximately equal spacing around the entire circumference of the projection of the steel sphere in the image. A circle was fit to the points and the diameter was set to 25.4 mm to scale the image. Second, two lines were drawn across the femoral shaft, one 8 cm and the other 12 cm proximal to the distal femoral joint line (Fig. 1). A third line connecting the midpoints of these two lines defined the femoral anatomic axis. Third, four points were digitized on the patella in full extension: the most superior and most posterior point, the most superior and most anterior point, the most inferior and most posterior point, and the most inferior and most anterior point. One line was drawn connecting the two superior points and another was drawn connecting the two inferior points. A third line connecting the midpoints of these two lines defined the patellar anatomic axis, and the midpoint of the patellar anatomic axis was the patella center [19, 39]. The patellar flexion angle was defined as the angle made by the femoral and patellar anatomic axes in both knees [17] (Fig. 1). These same points were digitized on images of the KA TKA and native contralateral knees at 30°, 60°, 90°, and maximum flexion.

For the KA TKA knee, the polyethylene patellar implant is invisible in fluoroscopic images, and therefore, the femoral component and patella do not appear to be in contact in early flexion. To determine the patellar contact location, a set of points was digitized along the anterior surface of the femoral component and posterior surface of the patella. Fourth-order polynomial curves were best-fit to each set of points and one thousand points were evenly distributed along each curve. In the case where the image was not truly lateral, an ellipse was best-fit to the resected surface of the patella, and the major axis of the ellipse defined the patellar curve. The Euclidian distance between each point on the femoral curve and each point on the patellar curve was then computed. The point on the patellar curve corresponding to the minimum computed distance from the femoral curve defined the patellar contact location, and the minimum distance was saved for use in the computation of patellar separation distance as described below. In deep flexion, the patella slides between the femoral condyles and the patella bone and femoral component appear to be in contact. In these cases, the most proximal and most distal points of contact between the patella bone and femoral component were digitized, as were points along the anterior surface of the femoral component between these two points. The area defined by these points was enclosed and the centroid of the enclosed area defined the patellar contact location [17, 20] (Fig. 2).

For the native contralateral knee, the entire femur and patella are visible. Points were digitized around the area of overlap between the femur and patella, and the centroid of this area defined the patellar contact location. The proximal–distal patellar contact locations were expressed as the distance along the patellar axis from the patella center to the patellar contact location, positive proximal (Fig. 2). All data were standardized to the mean length of the patellar axis for all patellae, which was 33 mm.

The patellar separation distance was computed as the thickness of the implanted patellar component subtracted from the minimum distance between the femoral curve and the patellar curve as described above, which corresponds to the minimum distance between the anterior surface of the femoral component and the resected surface of the patella

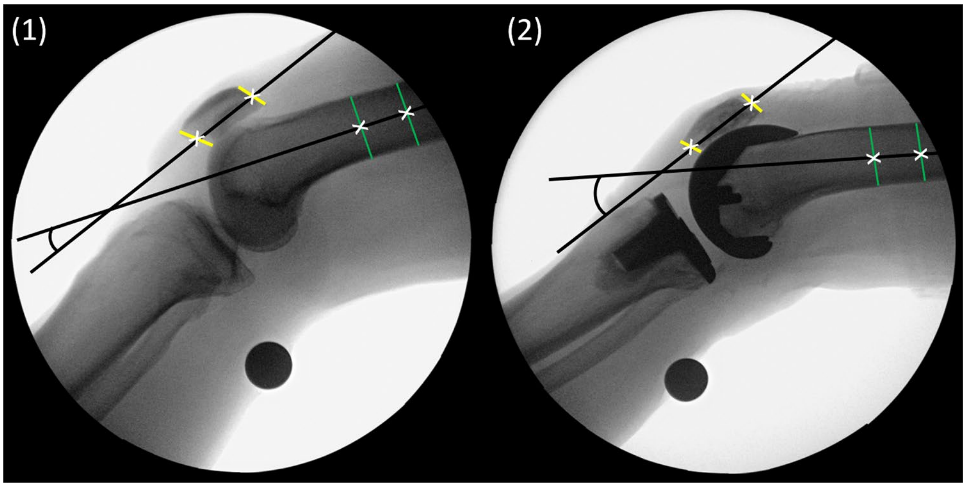

Fig. 1 Fluoroscopic images at 30° of flexion show the construction lines used to define the femoral and patellar anatomic axes in the native contralateral knee (1) and in the KA TKA knee (2). The angle between the femoral and patellar anatomic axes defined the patellar flexion angle

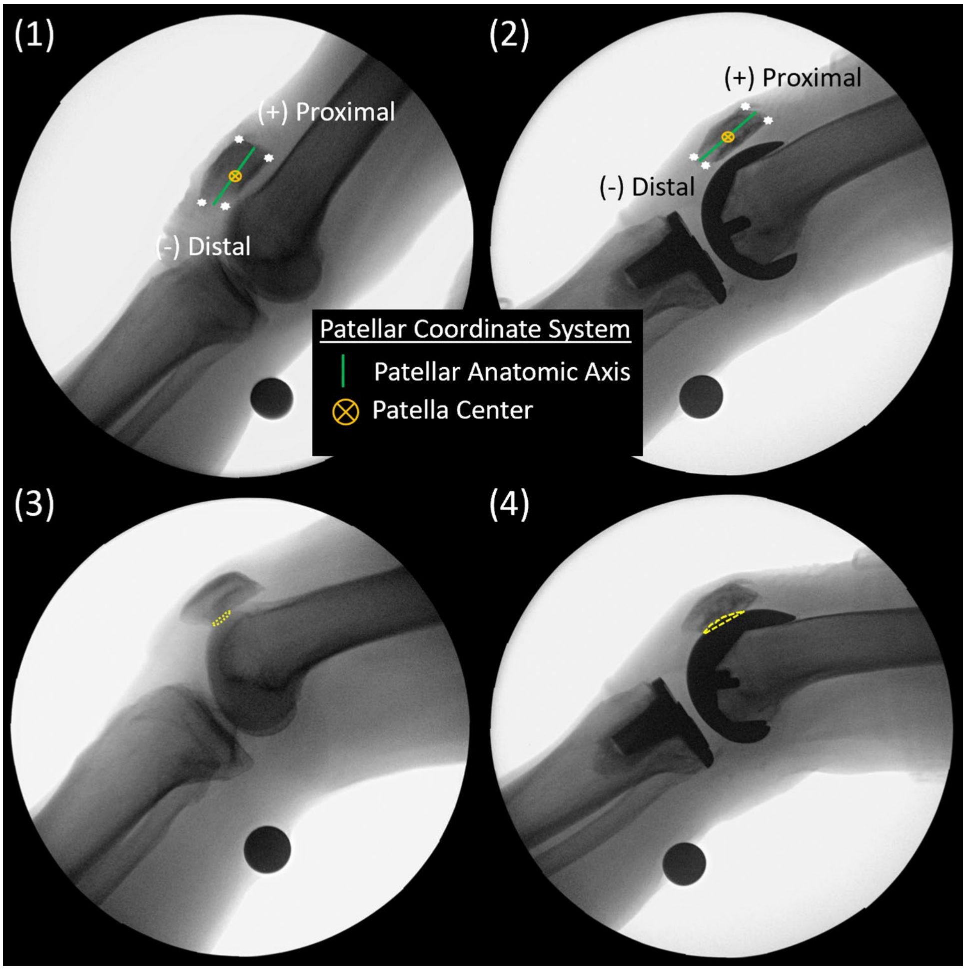

Fig. 2 Fluoroscopic images at full extension (top row) show the points digitized on the patella at full extension to define the patellar coordinate system (i.e. patellar anatomic axis and patella center) in the native contralateral knee (1) and in the KA TKA knee (2). The same points were digitized throughout flexion to define the patellar coordinate system consistently. Fluoroscopic images at 30° of flexion (bottom row) show the areas of overlap in the native contralateral knee (3) and in the KA TKA knee (4) whose centroids defined the proximal–distal patellar contact locations

(Fig. 3). Patellar loss of contact at full extension in the KA TKA knees occurred if the patellar separation distance was greater than zero [20]. Analysis of patellar separation was not necessary at flexion angles greater than 0° because the forces on the patella from the extensor mechanism in flexion cause it to remain in contact with the femur.

Statistical analysis

The arithmetic mean and standard deviation described the overall patellar flexion angles and proximal–distal patellar contact locations at each knee flexion angle for both knee conditions, as well as the overall demographic data [age, body mass index (BMI), preoperative weight-bearing deformity, passive flexion and extension]. The median and range described the patient-reported outcome scores (Oxford Knee, Knee Society, Forgotten Joint, WOMAC, and UCLA scores). Paired *t* tests determined the differences in mean patellar flexion angles and mean proximal–distal patellar contact locations between the KA TKA and the native contralateral knees at each flexion angle.

A power analysis confirmed that with 25 patients, differences in the mean proximal–distal patellar contact location between the KA TKA knees and the native contralateral knees of 3.6 mm, which is 10% of the average proximal–distal length of the patellar articular surface measured intraoperatively on 92 patellae in a previous study [1], could be detected with $\alpha = 0.05$ and $(1 - \beta) \geq 0.80$ using a standard deviation of the differences in proximal–distal patellar contact locations of 6.3 mm. This value was obtained from the present study based on measurements from 10 patients and subsequently checked with measurements from all 25 patients.

An intraclass correlation coefficient (ICC) analysis was performed to determine the repeatability and reproducibility of the methods described above. Five patients were randomly selected and the analysis was performed on their native contralateral knee and KA TKA knee images from full extension to maximum flexion. Three observers performed the analysis five times with at least 24 h between trials. The patellar flexion angle and proximal–distal patellar contact location were computed for each trial and each observer, and a three-factor, mixed-model analysis of variance (ANOVA)

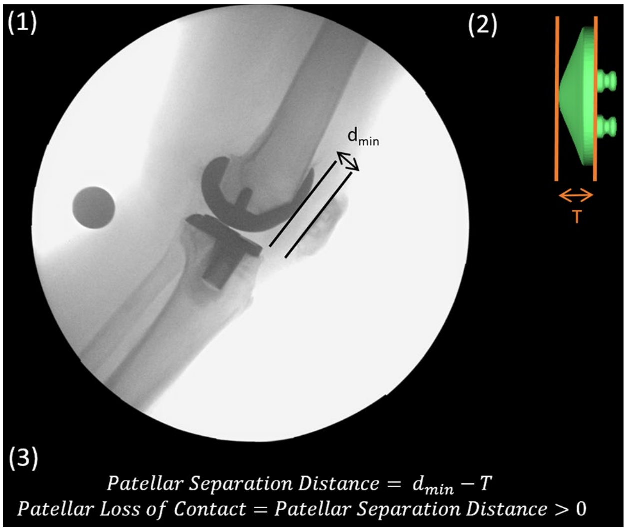

Fig. 3 Composite shows a fluoroscopic image at full extension for a patient who exhibited patellar loss of contact and the corresponding measurement of the minimum distance between the anterior surface of the femoral component and the resected surface of the patella (1), the measurement of the thickness of the patellar component (2), and the equations used to determine whether patellar loss of contact occurred (3)

was performed where the three factors were observer at three levels, patient at five levels, and flexion angle at five levels. Observer and patient were modeled as random effects, and flexion angle was modeled as a fixed effect (JMP, SAS Institute Inc., Cary, NC). The resulting variance components for observer, subject (patient), and error were used to compute the intraobserver and interobserver ICCs [3]. An ICC value of > 0.9 indicates excellent agreement, 0.75–0.90 indicates good agreement, 0.5–0.75 indicates moderate agreement, and 0.25–0.5 indicates fair agreement [15].

Results

There were no statistically significant differences in the mean patellar flexion angles between the KA TKA knees and the native contralateral knees ($p > 0.05$). From full knee extension to maximum knee flexion, the mean patellar flexion angle in the KA TKA knees exhibited a progressive increase from 9° to 83°. From full knee extension to maximum knee flexion, the mean patellar flexion angle in the native contralateral knees exhibited a similar pattern of progressive increase from 12° to 86° (Fig. 4).

At 0° of flexion, the mean proximal–distal patellar contact location of the KA TKA knees was 4 mm proximal to that of the native contralateral knees ($p = 0.022$). From full extension to maximum flexion, the mean proximal–distal patellar contact location in the KA TKA knees exhibited progressive proximal translation from – 8 to 4 mm. The mean proximal–distal patellar contact location in the native contralateral knees exhibited a similar pattern of progressive proximal translation from – 12 to 2 mm between 0° and 60° of flexion, and then remained relatively centered from 60° to maximum flexion (Fig. 5).

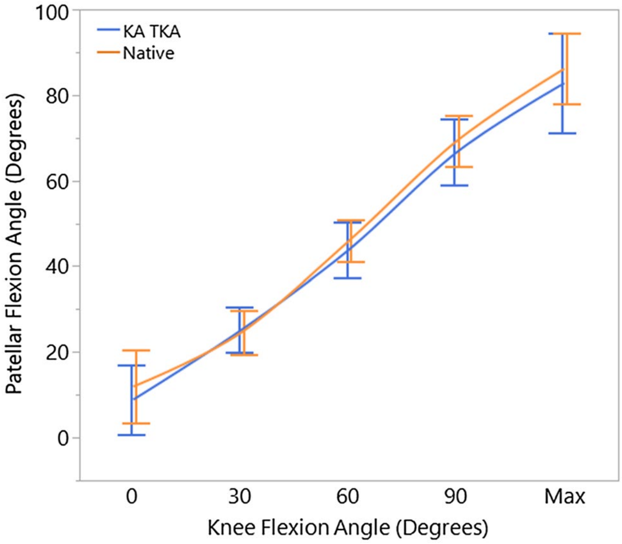

Fig. 4 Line plots show the mean and standard deviation of the patellar flexion angle at each knee flexion angle for the KA TKA knees and native contralateral knees from 0° to maximum flexion

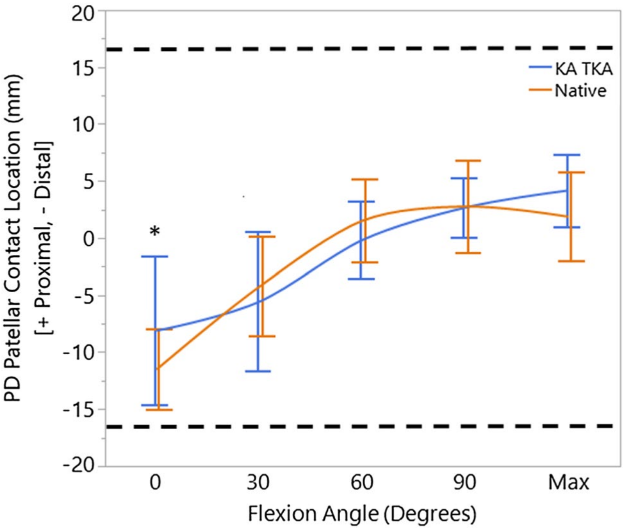

Fig. 5 Line plots show the mean and standard deviation of the proximal–distal (PD) patellar contact locations at each flexion angle for the KA TKA knees and native contralateral knees from 0° to maximum flexion. The asterisk at 0° of flexion indicates that the patellar contact location of the KA TKA knees was 4 mm more proximal than that of the native contralateral knees ($p < 0.05$). Dashed lines at ± 16.5 mm show the mean proximal–distal boundaries of all patellae

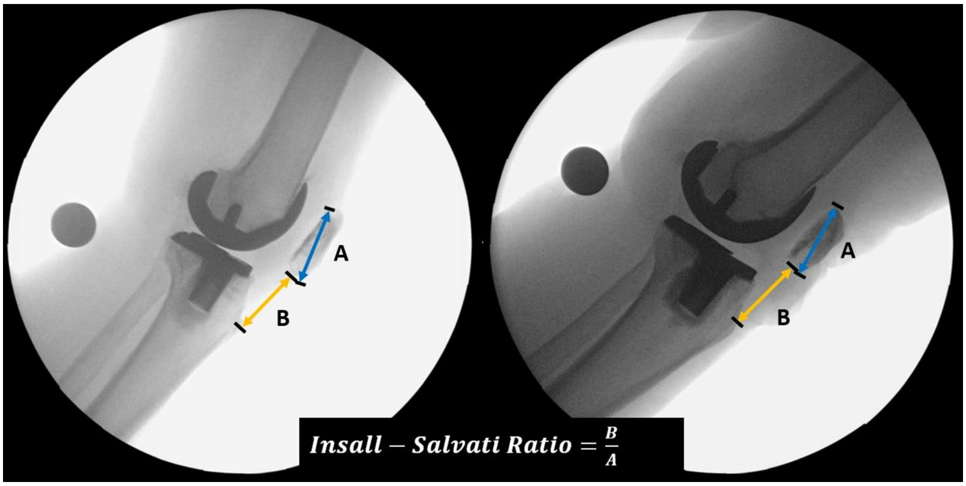

Fig. 6 Fluoroscopic images at full extension for the two patients who exhibited patellar loss of contact. The Insall–Salvati ratio was measured for both patients as the ratio of the distance from the patellar tendon's insertion site on the tibial tubercle to its origin on the inferior pole of the patella (B) to the greatest diagonal length of the patella (A)

The incidence of patellar loss of contact at full extension was 8% (2 of 25 patients) (Fig. 6). The patellar separation distances were 1.5 mm and 1.6 mm. The mean maximum flexion reached during the deep knee bend, as measured by the limb which reached the smaller maximum flexion angle, was 105° ± 11° (range 90°–120°).

The median patient-reported outcome scores were 46 for the Oxford Knee Score (range 28–48), 3 for the WOMAC (range 0–43), 75 for the Forgotten Joint Score (range 2–100), 140 for the Knee Society Score (range 80–150), and 7 for the UCLA Score (range 5–10) (Table 1).

The ICC values for repeatability (i.e. intraobserver) and reproducibility (i.e. interobserver) for both native contralateral knees and KA TKA knees ranged from 0.78 to 0.89 for patellar flexion angle and proximal–distal patellar contact location, except for proximal–distal patellar contact location in the native contralateral knees, which was 0.60 for both repeatability and reproducibility. Accordingly, the repeatability and reproducibility for the method for computing proximal–distal patellar contact location in the native contralateral knees was rated as moderate agreement, and all other methods were rated as good agreement. The repeatability errors for a representative observer were 0.9°, 1.6°, 2.6 mm, and 4.3 mm for patellar flexion angle and proximal–distal patellar contact location in the KA TKA knees and the native contralateral knees, respectively.

Discussion

The present study determined whether the patellar flexion angle and proximal–distal patellar contact location of a KA TKA performed with anatomic, fixed-bearing, PCR components were different from those of the native contralateral knee during a deep knee bend and determined the incidence of patellar loss of contact at full extension for KA TKA only. The most important findings were that (1) there were no statistically significant differences in mean patellar flexion angles between the KA TKA knees and the native contralateral knees, (2) statistically significant differences in mean proximal–distal patellar contact locations between the KA TKA knees and the native contralateral knees were limited to 4 mm, and (3) the incidence of patellar loss of contact in the KA TKA knees at full extension was 8% (2 of 25 patients).

No differences in mean patellar flexion angle were observed between the KA TKA knees and the native contralateral knees (Fig. 4). Intuitively, this may be a consequence of having restored the joint lines of the KA TKA knees to native and hence restored the resting lengths of the soft tissues, which is the goal of KA TKA. Conversely, joint line elevation is associated with patella baja, reduced range of motion, increased patellar flexion angle, and poor clinical outcomes [8, 18]. The progressive increase in patellar flexion angle with increasing knee flexion angle observed in the present study is consistent with previous studies in MA TKA [17, 20]. However, the present study showed no significant differences in patellar flexion angles between the KA TKA knees and the native contralateral knees at any knee flexion angle, while the native group rotated significantly more than the MA TKA group in deep flexion in a previous study [20]. The differences between the present study and the previous study of MA TKA could be a consequence of different implant designs, age differences between the TKA and native knee groups, surgical alignment technique, or a combination thereof.

Regarding surgical alignment technique, it is important to note the differences between KA TKA and MA TKA and how these differences may impact patellofemoral interaction. KA TKA and MA TKA are based on two different paradigms of implant positioning that use the same TKA components [32]. KA TKA is based on a patient-specific alignment paradigm that corrects the arthritic deformity to the pre-arthritic or constitutional alignment, which varies widely from 12° varus to 16° valgus among the world populace [38]. KA TKA strives to set the femoral and tibial components coincident with the native tibial–femoral articular surfaces, thereby restoring the native joint lines, limb alignment, knee laxities, and tibial compartment forces without ligament release [6, 33, 34, 37]. MA TKA is based on an average alignment paradigm that changes the constitutional alignment to a neutral hip–knee–ankle angle of 0°. MA TKA changes the native joint lines, limb alignment, knee laxities, and tibial compartment forces by aligning the components perpendicular to the mechanical axes and by externally rotating the femoral component with respect to the posterior femoral joint line [7, 9, 38]. Hence, the KA TKA and MA TKA varus–valgus and internal–external rotations of the prosthetic trochlea are different. A study of three femoral component designs found that KA TKA more closely restored the native medial–lateral location and radial location of the trochlea than MA TKA, which in turn more closely restores the *Q* angle and quadriceps moment arm [21]. Closer restoration of the native trochlea, particularly in the radial direction, may partially explain the smaller differences in patellar flexion angle from native observed in the present study of KA TKA compared to previous studies of MA TKA [19, 20, 39].

The latest and most compelling support for use of kinematic or an ‘individualized’ alignment paradigm in place of mechanical alignment is based on the new systematic classification of the phenotypes of the native limb and knee joint line [11]. 3D-reconstructed CT images confirmed the great variability of the coronal alignment of the lower limb and joint lines in both non-osteoarthritic [23] and osteoarthritic knees [10]. The currently used classification system (neutral, varus, valgus) oversimplifies the coronal alignment, and should be replaced by the use of femoral and tibial phenotypes. The detailed phenotype assessment of a patient’s individual anatomy justifies the individualized approach to TKA of restoring the native joint lines and limb alignment, which is the goal of KA TKA.

The difference in the mean proximal–distal patellar contact location between the KA TKA knees and the native contralateral knees was 4 mm when statistically significant (Fig. 5). This difference may not be clinically important because it is limited to only about 10% of the mean proximal–distal length of all patellae. Further, this difference placed the mean proximal–distal patellar contact location in the KA TKA knees proximal to that of the native contralateral knees, and therefore, closer to the center of the patella and patellar component (Fig. 5), which could be mechanically advantageous for the resurfaced patellae. The patellar component currently under study was dome-shaped, and therefore, thicker near the center of the component than near the edges. Further, the edges of the dome-shaped geometry are convex and not designed to conform to the surfaces of the medial and lateral femoral condyles in flexion (Fig. 3). Both component thickness and conformity are factors in polyethylene implant wear because higher contact stresses develop where the implant is thinner or non-conforming as shown in patellar component retrieval studies [5, 35]. Accordingly, having a proximal–distal patellar contact location closer to the center of the patellar component as seen here is desirable given the design of the patellar component under study.

The pattern of proximal translation of the mean patellar contact locations with knee flexion and the proximal position of the mean KA TKA knee patellar contact location relative to that of the native contralateral knee at 0° of flexion in the present study are consistent with previous studies of proximal–distal patellar contact locations in MA TKA with posterior cruciate-retaining components [19, 20, 39]. However, the differences between the KA TKA knees and native contralateral knees in the present study are smaller than those of the previous studies of MA TKA, particularly in early flexion. This may be explained by the factors previously described for the patellar flexion angle, particularly that KA TKA more closely restores the native trochlea in the medial–lateral and radial directions than MA TKA [21].

The incidence of patellar loss of contact at full extension for the KA TKA knees was 8% (2 of 25 patients). The magnitudes of the patellar separation distance were 1.5 mm and 1.6 mm. One potential contributing factor to the occurrence of patellar loss of contact is patella alta. A patient with patella alta, or a patellar tendon which is more than 1.2 times longer than the proximal–distal length of their patella per the Insall–Salvati ratio [16], may be predisposed to patellar loss of contact because their patella sits proximal to the trochlear groove, and therefore, would not be able to maintain patellofemoral contact at full extension. Accordingly, the Insall–Salvati ratio was measured (Fig. 6) and determined to be 0.99 for both patients, indicating that patella alta is not a contributing factor. Another potential contributing factor is an understuffed trochlea. The features of current implants are designed specifically to facilitate early patella capture and reduce constraint of patellar tracking throughout flexion for MA TKA. A study comparing the trochlea of the native knee and the KA TKA knee with the same femoral component used in this study (Persona CR, Zimmer-Biomet) found substantial understuffing of the proximal prosthetic trochlea [31]. However, given that all patients in this study had the same femoral component design and only 8% exhibited patellar loss of contact, understuffing of the trochlea does not fully explain this phenomenon. A final contributing factor is the posterior slope of the tibial resection. A steeper slope would create an anterior component of the tibial contact force during weight bearing which could displace the tibia anteriorly in a relatively lax knee leading to patellar loss of contact. The average posterior slope of the 25 patients studied was 6°; the posterior slopes of the two patients in

Fig. 6 were 6° and 9° for left and right images, respectively. Hence the larger slope for the patient in the right image may explain in part the loss of patellar contact.

Patellar loss of contact at full extension in TKA has been considered a dependent variable of interest in previous studies in part because it was not observed in the native knee, and because it was hypothesized to contribute to certain clunks that some patients experience, as well as potentially resulting in high impulse-type forces when the knee flexes and the patellar component regains contact with the femoral component [19, 20, 39]. However, the direct clinical relevance of the incidence of patellar loss of contact is unknown to date. Given the infrequent incidence of patellofemoral complications in KA TKA [26] and the results of a retrospective study of 222 knees (217 patients) treated with KA TKA which showed implant survivorship of 97.5% at 10 years of follow-up [14], it is possible that patellar loss of contact is not predictive of patellofemoral complications in KA TKA.

There were several limitations to this study. First, this study considered one anatomic, fixed-bearing, PCR implant design (Persona CR, Zimmer-Biomet, Warsaw, IN). Implant design and presence or absence of the posterior cruciate ligament (PCL) are important independent variables in the study of patellar flexion angle, proximal–distal patellar contact location, and patellar loss of contact at full extension [20, 39] and therefore, these results may not be generalizable to KA TKA performed with different implants. Second, patellar contact occurs in two regions (i.e. on the medial and lateral facets) and the present study approximated the midpoint of these regions of contact in the proximal–distal direction of the sagittal plane. Accordingly, it is possible that these results are not generalizable to studies which perform the analysis in three dimensions. Third, although the initial image was truly lateral with the posterior femoral condyles superimposed, the natural internal–external rotation of the tibia on the femur with flexion often resulted in images which were not lateral in deeper flexion. An in vitro error analysis was performed in a previous study in which five cadaveric TKA patellae and femoral components were abducted, adducted, internally rotated, and externally rotated relative to one another to simulate this variability. The errors in computing the patellar flexion angle, proximal–distal patellar contact location, and patellar separation distance were 0.52°, 0.71 mm, and 0.38 mm, respectively [39]. Finally, a selection bias might have occurred if the patients who gave informed consent had more favorable outcomes than those who did not give informed consent. To assess this possibility, the mean Oxford Knee Score from our study was compared to those from other studies involving patients with KA TKA. Our mean score of 44 was nearly identical to those of other studies which reported means of 44 at 15 months [27] and 42 at 6 months [13, 25]. Given the close agreement between the mean Oxford Knee Scores, it is unlikely that patient selection affected our results.

Conclusion

Calipered KA TKA performed with anatomic, fixed-bearing, PCR components restored mean patellar flexion angles to those of the native contralateral knee and largely restored the proximal–distal patellar contact locations, which at most differed from those of the native contralateral knee by approximately 10% of the mean proximal–distal patellar length. The incidence of patellar loss of contact at full extension was infrequent at 8% (2 of 25 patients). These results are consistent with the infrequent reports of patellofemoral complications following KA TKA [14, 26], as well as a prosthetic trochlea which was more closely restored to native with a kinematically aligned femoral component compared to one which was mechanically aligned [21].

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Compliance with ethical standards

Conflict of interest S.M. Howell is a paid consultant for THINK Surgical and Medacta, Inc. M.L. Hull receives research support from Zimmer-Biomet and Medacta, Inc. Remaining authors declare that they have no conflict of interest.

Ethical approval This study was approved by the University of California Davis Institutional Review Board (IRB#954288).

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