Analysis of Differences in Laxities and Neutral Positions From Native After Kinematically Aligned TKA Using Cruciate Retaining Implants

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ABSTRACT: One biomechanical goal of kinematically aligned total knee arthroplasty (KA TKA) is to achieve knee laxities and neutral positions that are not different from those of the native knee without soft tissue release. However, replacing the articular surfaces and menisci with implants of discrete sizes and average shapes and resecting the anterior cruciate ligament (ACL) might prevent KA TKA from achieving this goal in the tibiofemoral joint. Accordingly, the objective was to determine whether either or both surgically induced changes cause differences in laxities and/or neutral positions from native using a cruciate retaining implant. Eight laxities and four neutral positions were measured from 0° to 120° flexion in 30° increments in 13 human cadaveric knees in three knee conditions: native, ACL-deficient, and KA TKA. After KA TKA, 5 of the 40 laxity measures (8 laxities × 5 flexion angles) and 6 of the 20 neutral position measures (4 neutral positions × 5 flexion angles) were statistically different from those of the native knee. The greatest differences in laxities from native after KA TKA occurred at 30° flexion in anterior translation (1.6 ± 2.1 mm increase, $p < 0.0001$); this difference was 1.7 ± 2.1 mm less than that in the ACL-d knee ($p < 0.0001$). The greatest difference in neutral positions from native after KA TKA occurred in anterior–posterior translation at 0° flexion (3.8 ± 1.9 mm anterior, $p < 0.0001$); this difference was 2.6 ± 1.9 mm greater than that in the ACL-d knee ($p = 0.0002$). *Clinical Significance*: These results indicate that the biomechanical goal of KA TKA is largely realized despite the two surgically induced changes. © 2018 Orthopaedic Research Society. Published by Wiley Periodicals, Inc. J Orthop Res 37:358–369, 2019.

Keywords: joint stability; resting position; total knee replacement; component alignment; passive biomechanics

One outcome goal of kinematically aligned total knee arthroplasty (KA TKA) is to restore objective metrics of biomechanical function such that they are not different from those of the native (i.e., pre-arthritic) knee.[1,2] To achieve this outcome goal, the surgical goal of KA TKA is to align the femoral and tibial components to restore the native joint lines (i.e., lines tangent to the distal femoral condyles and the tibial plateau in the coronal plane, to the posterior femoral condyles in the axial plane, and to the medial tibial plateau in the sagittal plane), which in turn should restore the native alignments of the limb and knee without soft tissue release.[1,2] By doing so, KA TKA might limit differences in biomechanical function from native.[3–5] Native biomechanical function encompasses both passive knee biomechanics (e.g., laxities and neutral or resting positions) and active knee biomechanics (e.g., kinematics and stability during gait, deep knee bend, kneeling, etc.). Although high rates of patient satisfaction have been reported at 6 months to 6 years post-operatively,[6,7] there are two surgically induced changes that might cause biomechanical function of cruciate retaining KA TKA to differ from native. These are (i) the replacement of the articular surfaces and menisci with implants of discrete sizes and average shapes and (ii) the resection of the anterior cruciate ligament (ACL).

These two surgically induced changes may cause differences in the passive biomechanics of the tibiofemoral joint after KA TKA from native because the passive biomechanics are determined by the interaction between the articular geometry and the soft tissue restraints.[8–10] Two important metrics commonly used to characterize passive biomechanics[8–19] are laxities and neutral positions. The laxities are a measure of the constraint provided by both the articular surfaces and the soft tissue restraints.[8] The neutral positions over the full arc of flexion are a measure of the passive kinematics guided by the interaction between the shapes of the articular surfaces and the soft tissue restraints.[9,10]

How each of the two surgically induced changes affects the passive biomechanics of the tibiofemoral joint can be assessed by measuring the laxities and neutral positions of the native knee, the ACL-deficient (ACL-d) knee, and the KA TKA. It is necessary to perform this assessment in vitro rather than in vivo because the knee is not in a native condition in vivo when KA TKA is performed. Based on pairwise comparisons between the laxities and neutral positions of the native knee, the ACL-d knee, and the KA TKA, one of five possible explanations about the effect of the two surgically induced changes on the differences in the laxities and neutral positions after KA TKA from native can be reached (Fig. 1).

Accordingly, the objectives of the present study were to determine whether either or both surgically induced changes after KA TKA caused (i) differences in eight laxities in four degrees of freedom including

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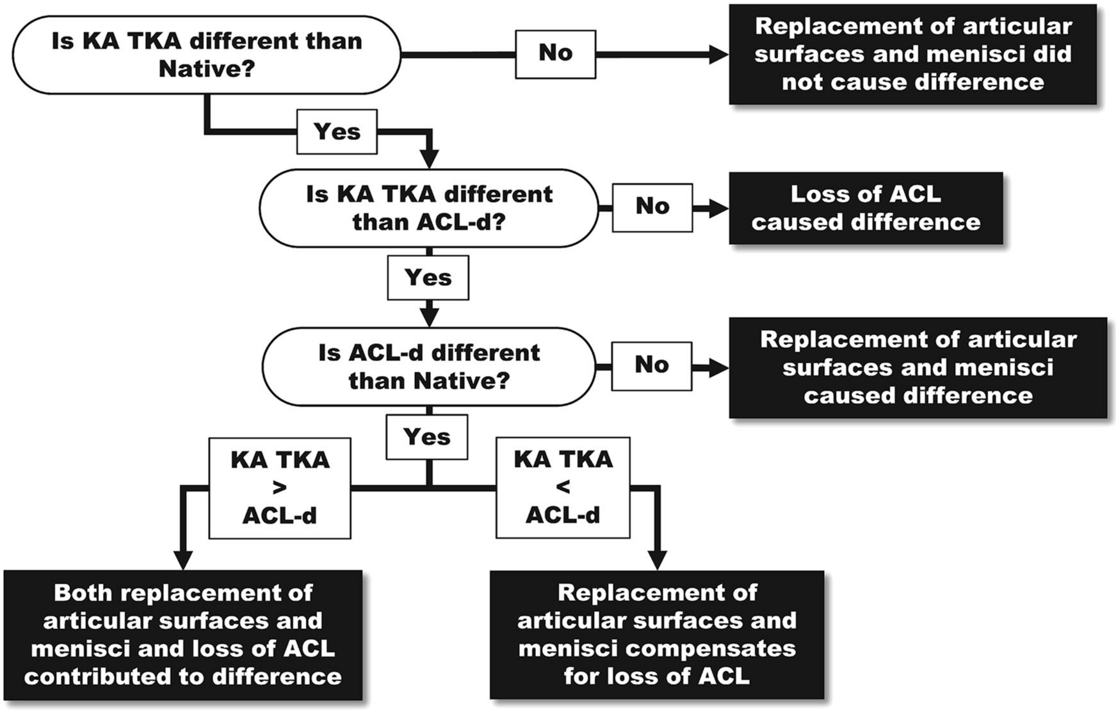

Figure 1. Flowchart shows how five possible explanations for differences in any of the eight laxities or four neutral positions are reached by comparing the laxities and neutral positions of the native knee, the anterior cruciate ligament-deficient (ACL-d) knee, and the kinematically aligned total knee arthroplasty (KA TKA).

varus-valgus (V-V) rotation, internal–external (I-E) rotation, anterior–posterior (A-P) translation, and compression-distraction (C-D) relative to those of the native knee and ACL-d knee and (ii) differences in the four neutral positions (one in each of the four degrees of freedom) relative to those of the native knee and ACL-d knee. These objectives were of interest to objectively assess the efficacy with which KA TKA satisfies the outcome goal when using a cruciate retaining implant design.

MATERIALS AND METHODS

Thirteen fresh-frozen human cadaveric knee specimens were included (mean age = 83 years, range = 65–98 years). Before inclusion, each specimen was screened using an anteroposterior radiograph of the knee. Specimens were excluded when there were signs of degenerative joint disease (i.e., marginal osteophytes, joint space narrowing, chondrocalcinosis, and/or subchondral sclerosis) and/or evidence of previous surgery to the knee. An a priori power analysis determined that effect sizes greater than or equal to 0.85 could be detected using 13 knee specimens with $\alpha = 0.05$ and $(1\text{-}\beta) = 0.8$. Using the maximum standard deviations of the differences in laxities and neutral positions between the KA TKA and the native knee determined in the present study, mean differences as small as 1.1° in the V-V laxities, 0.7° in the V-V neutral position, 2.9° in the I-E laxities, 3.1° in the I-E neutral position, 1.8 mm in the A-P laxities, 3.1 mm in the A-P neutral position, 0.7 mm in the C-D laxities, and 1.0 mm in the C-D neutral position could be detected.

Each knee was prepared for testing using the following dissection procedure. First, the fibula was rigidly fixed to the tibia using a transverse screw 12 cm below the joint line to retain the rigidity of both the tibiofibular joint and the insertions of the lateral collateral ligament and biceps femoris tendon. Second, the thigh was transected 20 cm proximal to the tibial plateau and the shank was transected 25 cm distal to the tibial plateau. Third, all soft tissues more than 15 cm proximal and 12 cm distal to the tibial plateau were removed. Fourth, the fibula was transected just distal to the transverse screw fixing it to the tibia. Fifth, all skin and subcutaneous adipose tissue were removed. Sixth, the tendons of insertion of the biceps femoris, semimembranosus, semitendinosus, and quadriceps were isolated, and the semimembranosus and semitendinosus tendons were sutured together. Seventh, cloth loops were sutured to the tendons of insertion of the biceps femoris, the semimembranosus and semitendinosus (grouped together), and the quadriceps. Finally, intramedullary rods were cemented into the medullary canals of both the femur and tibia, and each knee was loosely wrapped in saline-soaked gauze to prevent dehydration of the tissues.

Following dissection, each knee was aligned in a six degree-of-freedom load application system[20] using alignment fixtures so that the flexion-extension (F-E) and I-E rotation axes of the load application system were coincident with the F-E and longitudinal rotation axes of the tibiofemoral joint as described previously[11] (Fig. 2). Briefly, the intramedullary rods were connected to the alignment fixtures that allowed six degree-of-freedom adjustments of both the femur and tibia relative to the load application system. Alignment of the axes of the tibiofemoral joint with those of the load application system was achieved when the coupled motions to both F-E rotation from 10° to 110° (i.e., A-P and proximal-distal translations and V-V rotation) and I-E rotation between about ±10° of rotation at 30° of flexion (i.e., A-P and medial-lateral translations and V-V rotation) were minimized (i.e., A-P and medial-lateral ≤ 1 mm, proximal-distal ≤ 5 mm,

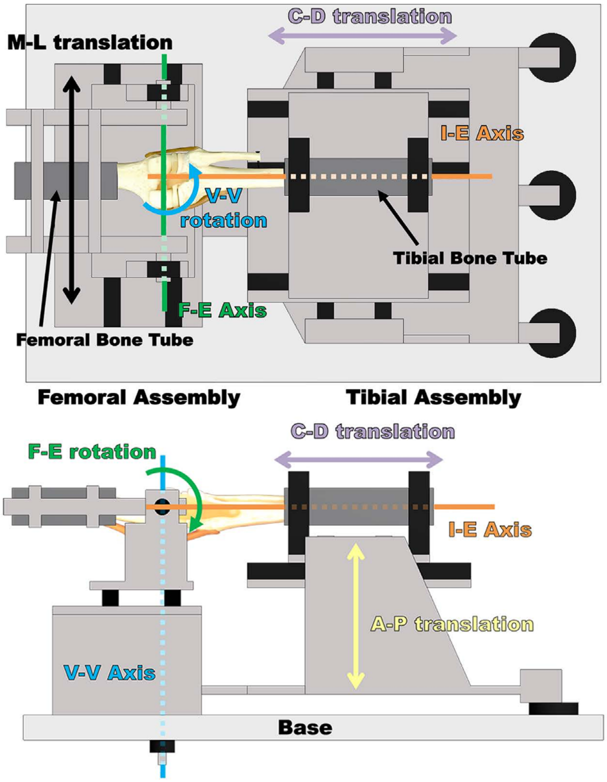

Figure 2. Schematic of the six degree-of-freedom load application system[20] used to flex and extend the knee. The knee specimen is mounted in the load application system with the patella toward the base. A functional alignment procedure aligns the flexion-extension (F-E) and longitudinal rotation (i.e., internal–external rotation [I-E]) axes of the tibiofemoral joint with the F-E and I-E axes of the load application system. The degrees of freedom follow the coordinate system of Grood and Suntay[49] so that the flexion-extension axis is fixed to the femoral assembly, and the longitudinal rotation axis is fixed to the tibial assembly. Accordingly, the femoral assembly provides two degrees of freedom, F-E rotation and medial-lateral (M-L) translation. The tibial assembly provides the remaining four degrees of freedom including I-E and varus-valgus (V-V) rotations and anterior–posterior (A-P) and compression-distraction (C-D) translations. Stepper motor actuators (omitted for clarity) apply loads in all degrees of freedom except M-L translation. Unconstrained motions in all degrees of freedom are enabled through the use of low-friction bearings.

and V-V ≤ 1°[11]). Once alignment was confirmed, the femur and tibia were potted within square aluminum tubes using methyl methacrylate to fix the position and orientation of each bone relative to the load application system during testing.

Prior to testing, each knee was subjected to a preconditioning protocol consisting of first cycling the knee five times between ±2.5 Nm in F-E and then extending the knee under 2.5 Nm to define 0° of flexion (i.e., full extension).[21] Next the knee was moved to a flexion angle randomly selected from 0°, 60°, and 120° and then cycled five times between the prescribed loads for each degree of freedom in a random order[22]; the prescribed loads for each degree of freedom were ±3 Nm for I-E,[8] ±5 Nm for V-V,[19] ±45 N for A-P,[23] and ±100 N for C-D.[18] The magnitude of each load was set to just engage the soft tissue restraints (i.e., load to the onset of the high/terminal stiffness region of the tibiofemoral joint's load-deformation curve in each degree of freedom[19,23]). The preconditioning protocol was repeated for the other two flexion angles also in a random order.

After preconditioning, the eight laxities and four neutral positions were measured in the native knee using the six degree-of-freedom load application system.[20] Throughout testing, small loads were applied to the tendons of the biceps femoris (15 N), the semimembranosus and semitendinosus (grouped together) (26 N), and the quadriceps (80 N) using constant force springs (Century Springs Corp., Commerce, CA; rated load tolerance of constant force springs = ± 10%). Both the quadriceps and medial and lateral hamstrings were loaded to maintain the inherent stability to the joint because subluxations were observed in some knees during pilot testing.[14,24] The relative magnitudes of these loads were proportional to the mean physiological cross-sectional area of each muscle, and each was about 3% of the maximum isometric force of that muscle group assuming a specific tension of 30 $^{\mathrm{N}}/_{\mathrm{cm}^2}$.[25,26] Each laxity and neutral position was measured over an arc of flexion from 0° to 120° in 30° increments. The order of the flexion angle-degree of freedom combinations was randomized. For each combination, the knee was loaded to the positive limit (A), loaded to the negative limit (B), unloaded (i.e., no applied loads other than the muscle loads) (C), loaded to the negative limit (D), loaded to the positive limit (E), and unloaded (F).[11,12] The positive and negative limits were defined under the same loads as those used during pre-conditioning. The neutral position was computed as the mean of the two unloaded positions (C and F) of the tibia relative to the femur. Each laxity was computed as the difference between the mean position of the tibia relative to the femur under either the positive (A and E) or negative (B and D) load and the neutral position.

After testing the native knee, it was removed from the load application system, and the ACL was transected. To access the ACL, the joint was exposed through a mid-sagittal osteotomy in the patella (i.e., the transpatellar approach[27]), which has been shown to have negligible effects on knee mechanics.[15,27] The ACL was transected at the tibial attachment using blunt nose scissors. The exposure was closed using two transverse screws in the patella and sutures in the quadriceps and patellar tendons. The ACL-d knee was re-mounted in the load application system in the same alignment as that of the native knee, and the laxities and neutral positions were re-measured using the same procedure as that described previously for the native knee. After testing was completed in the ACL-d knee, the knee was wrapped in fresh saline-soaked gauze and placed in a sealed plastic bag in the refrigerator at 4°C overnight.

The following day, a KA TKA was performed on the knee by a surgeon with expertise in the technique[28–30] (Fig. 3). The femoral and tibial components were aligned to the native joint lines as described elsewhere.[28–30] Kinematic alignment of the components was confirmed by the following quality assurance checks. The kinematic alignment of the femoral component (Zimmer Persona CR) in V-V, proximal-distal (P-D), I-E, and A-P was confirmed when the thickness of each of the four femoral resections (i.e., distal medial, distal lateral, posterior medial, and posterior lateral) measured using calipers (Zimmer Biomet, 1 mm increments, 0.5 mm resolution) was within 0.5 mm of that of the corresponding region of the femoral component after correcting for the kerf of the saw.[28–30] It is important to note that because cartilage wear was not present in these specimens, loss of cartilage thickness present in osteoarthritic patients did not have to be accounted for during

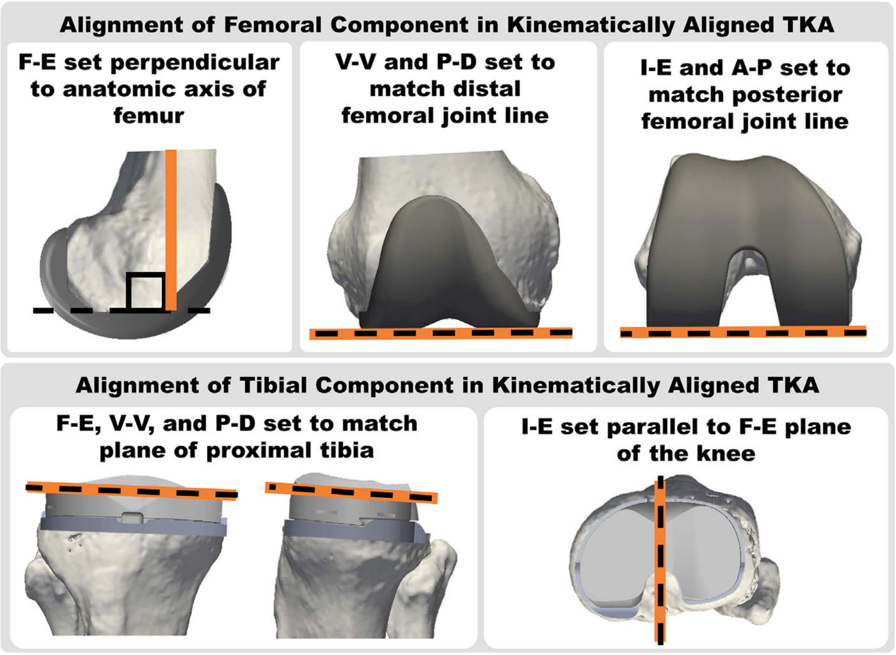

Figure 3. Composite illustrates the desired alignment of both the femoral component (top row) in flexion-extension (F-E), varus-valgus (V-V), internal–external rotation (I-E), proximal-distal (P-D), and anterior–posterior (A-P) and the tibial component (bottom row) in F-E, V-V, I-E, and P-D after kinematically aligned TKA. Each solid orange line represents the alignment target, and each dashed black line represents the feature of the component being aligned to the alignment target. Not shown are the medial-lateral position of the femoral component, which is set visually by the surgeon so as to center the component on the femur and the medial-lateral and A-P positions of the tibial component, which are set to minimize overhang.

these in vitro KA TKAs as it does in vivo.[28–30] When the thicknesses of the femoral resections were within 0.5 mm of the thicknesses of the corresponding regions of the femoral component, the joint lines of the femoral component closely matched those of the native knee.[1]

After kinematic alignment of the femoral component was confirmed, kinematic alignment of the tibial component (Zimmer Persona CR) in V-V, P-D, and F-E was confirmed when the knee was stable at 0° of flexion (i.e., had negligible V-V laxity at 0° of flexion indicated by negligible gapping medially and laterally during a manual laxity assessment as judged visually by the surgeon, which matches the that of the native knee[11,12]) and had the same A-P offset of the distal medial condyle of the femur from the anterior cortex of the tibia at 90° of flexion as that in the ACL-d knee before the distal femoral resections were made.[28–30] These checks have been shown clinically to result in a V-V orientation of the tibial component within $0.0^\circ \pm 1.8^\circ$ of that of the contralateral healthy knee[1] and a posterior slope within $-0.2^\circ \pm 2.5^\circ$ of the pre-operative posterior slope.[31] Correct thickness of the tibial insert was confirmed when the full extension position (i.e., flexion-extension orientation of the tibia relative to the femur when the femur and tibia are simply supported) matched that of the ACL-d knee before any resections were made.

After kinematic alignment of the components was confirmed, both femoral and tibial components were cemented in place. After the cement had cured, the exposure was closed as previously described. The KA TKA knee was re-mounted in the load application system in the same alignment as that of the native and ACL-d knees, and the laxities and neutral positions were re-measured using the same procedure as that described previously for both the native and ACL-d knees. Neither removal and re-mounting of the specimens nor testing over consecutive days introduced appreciable errors in to the measurements (Supplement 1).

Statistical Analysis

To determine whether either or both surgically induced changes after KA TKA caused differences in the eight laxities and the four neutral positions, a two-factor repeated measures analysis of variance (ANOVA) including interaction was performed for each dependent variable (JMP Version 11.2.0; SAS Institute Inc., Cary, NC; www.jmp.com). The first factor was knee condition at three levels (native, ACL-d, and KA TKA), and the second factor was flexion angle at five levels (0° to 120° in 30° increments). When an important interaction was observed in the ANOVA, post hoc pairwise comparisons between the treatment means ($\bar{Y}_{ij\cdot}$, mean over the 13 knees) of the native knee ($i = 1$), those of the ACL-d knee ($i = 2$), and those of the KA TKA ($i = 3$) were performed at each flexion angle ($j = 1, 2, 3, 4, 5$ for 0°, 30°, 60°, 90°, and 120° of flexion, respectively) using the Bonferroni method.[32] For the ANOVAs, the level of significance (α) was set at 0.05. For the *post hoc* pairwise comparisons using the Bonferroni method, the level of significance ($\alpha_{\mathrm{Bonferoni}}$) was set at 0.003 ($\alpha_{\mathrm{Bonferoni}} = \frac{\alpha}{g}$, where $g = 15$; 3 comparisons/flexion angle × 5 flexion angles). Differences with p-values less than the level of significance were considered statistically different.

RESULTS

After KA TKA, 5 of the 40 laxity-flexion angle combinations were statistically different from those of the native knees (Figs. 4–7). Three of these five laxity-

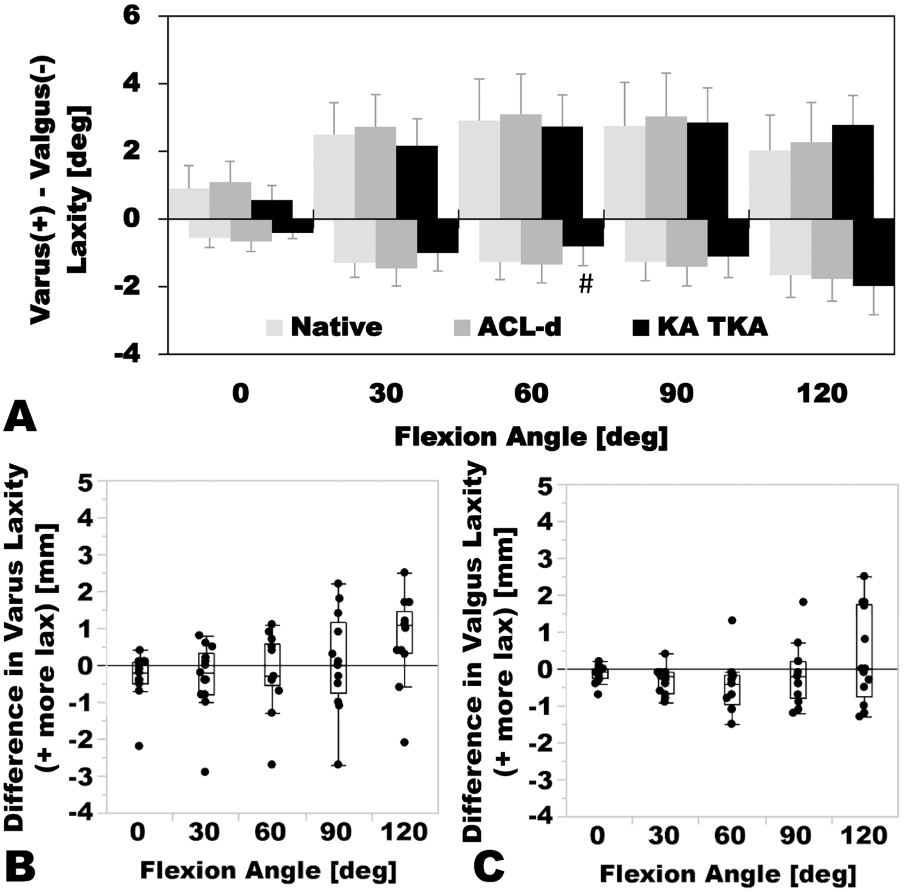

Figure 4. A vertical bar chart (A) shows the means (bars) and standard deviations (error bars) of the varus and valgus laxities of the native, ACL-d, and KA TKA knees. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the laxity of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots show the differences in the varus (B) and valgus (C) laxities after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

flexion angle combinations were in the I-E degree of freedom (Fig. 5, Table 1). The mean internal rotation laxities after KA TKA at 30° and 90° of flexion were greater than those of the native knee. The mean external rotation laxity after KA TKA at 30° of flexion was less than both that of the native knee and that of the ACL-d knee.

Another one of the five laxity-flexion angle combinations that was statistically different was in the A-P degree of freedom (Fig. 6, Table 1). The mean anterior translation laxity after KA TKA at 30° of flexion was greater than that of the native knee but was less than that of the ACL-d knee. The mean anterior translation laxity of the ACL-d knee at 30° of flexion was greater than that of the native knee.

The final one of the five laxity-flexion angle combinations that was statistically different was in the C-D degree of freedom (Fig. 7, Table 1). The mean distraction laxity after KA TKA at 120° of flexion was greater than that of the native knee and that of the ACL-d knee.

After KA TKA, 6 of the 20 neutral position-flexion angle combinations were statistically different from those of the native knees (Figs. 8–11). Two of the six neutral position-flexion angle combinations were in the I-E neutral position (Fig. 9, Table 2). The mean I-E neutral position after KA TKA was more internally rotated at 0° of flexion than that of the native knee. In contrast at 30° of flexion, the mean I-E neutral position after KA TKA was more externally rotated than that of both the native knee and the ACL-d knee.

The other four of the six neutral position-flexion angle combinations that were statistically different were in the A-P neutral position (Fig. 10, Table 2). The mean A-P neutral position after KA TKA was more anterior at 0° of flexion than that of both the native knee and the ACL-d knee. In contrast at 60°, 90°, and 120° of flexion, the mean A-P neutral positions after KA TKA were more posterior than those of both the native knee and the ACL-d knee.

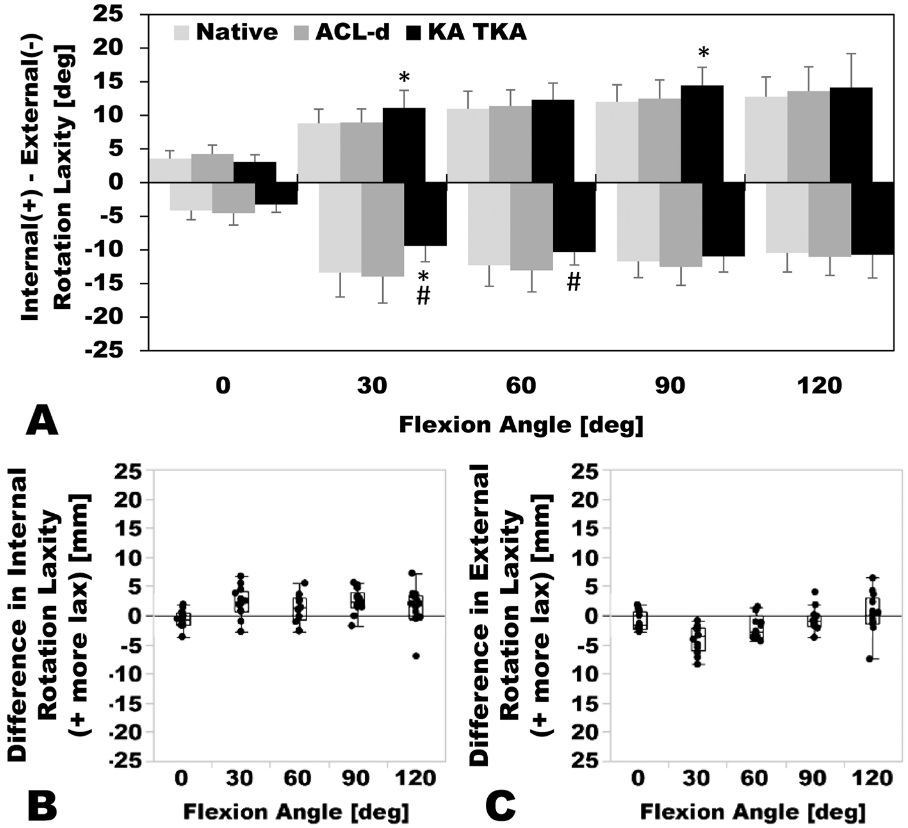

Figure 5. A vertical bar chart (A) shows the means (bars) and standard deviations (error bars) of the internal and external rotation laxities of the native, ACL-d, and KA TKA knees. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the laxity of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots show the differences in the internal rotation (B) and external rotation (C) laxities after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

DISCUSSION

Two surgically induced changes that might limit the efficacy with which cruciate retaining KA TKA satisfies the outcome goal of achieving passive biomechanics that do not differ from those of the native tibiofemoral joint are (i) the replacement of the articular surfaces and menisci with implants of discrete sizes and average shapes and (ii) resection of the ACL. To determine whether either or both surgically induced changes after KA TKA caused differences in passive biomechanics from native, the present study measured eight laxities and four neutral positions in three conditions of each knee (native, ACL-d, and KA TKA). The first key finding of this study was that after KA TKA 5 of 40 (12.5%) laxity-flexion angle combinations were statistically different from those of the native knees. The differences in the mean I-E, V-V, A-P, and C-D laxities from native after KA TKA were <4°, <1°, <2 mm, and <1 mm, respectively. The second key finding was that after KA TKA 6 of 20 (30%) neutral position-flexion angle combinations were statistically different from those of the native knees. The changes in the mean I-E, V-V, A-P, and C-D neutral positions from native after KA TKA were <5°, <1°, <4 mm, and <1 mm, respectively.

Prior to discussing the key findings, three limitations should be mentioned. The first limitation concerns the application of muscle forces. While ideally laxities and neutral positions would have been measured passively with no muscle forces applied, muscle forces were necessary to maintain stability in the tibiofemoral joint throughout flexion following TKA. Forces across the joint both reduce the contribution of the soft tissue restraints to maintaining joint stability[13] and the reduce the laxities; thus, the differences in the laxities might be greater without muscle forces. A second limitation is that this study was carried out in knees free from osteoarthritis. While this was necessary to answer the research questions posed in the present study as to whether KA TKA caused differences in laxities and neutral positions from native, these results may not translate directly into clinical practice where all knees will have end stage osteoarthritis. In osteoarthritic knees, the thickness of the worn articular cartilage must be estimated when making the femoral resections where the goal is have the resection thickness be equal to that of the femoral component after correcting for articular

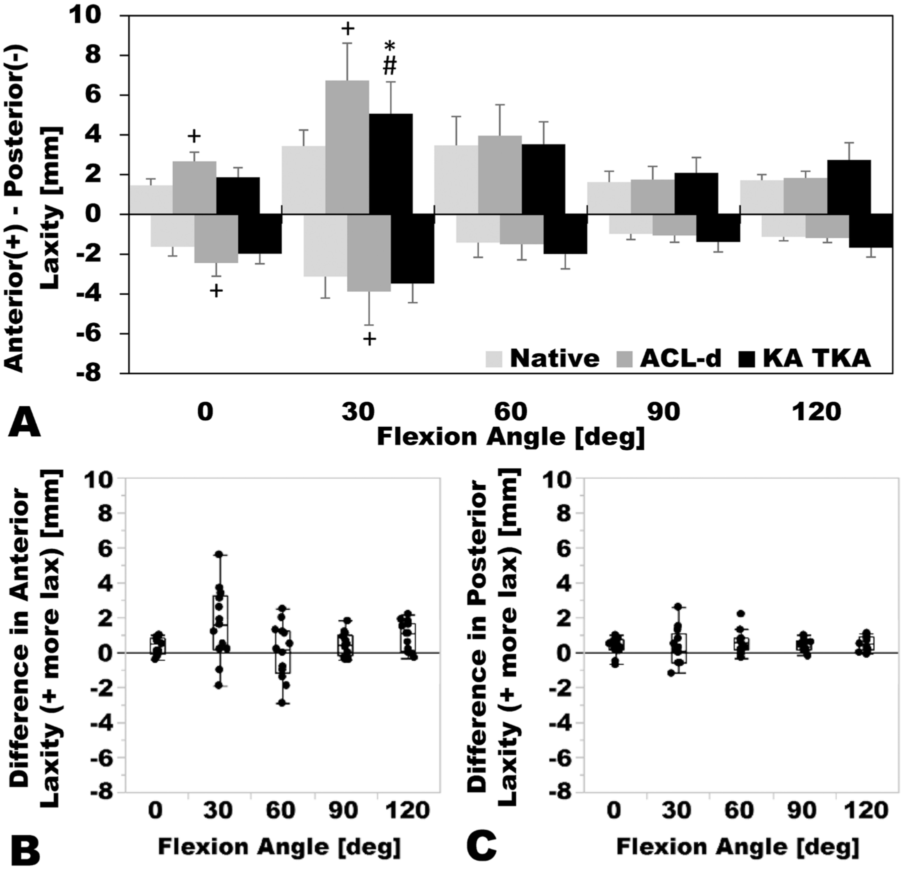

Figure 6. A vertical bar chart (A) shows the means (bars) and standard deviations (error bars) of the anterior and posterior translation laxities of the native, ACL-d, and KA TKA knees. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the laxity of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots show the differences in the anterior (B) and posterior (C) laxities after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

cartilage wear and kerf.[28,30] Also in osteoarthritic knees, it is possible that contracture or lengthening of the soft tissue restraints[33–35] might alter the coronal alignment of the tibial component and thus change the tibial joint line from native. A third limitation was that the changes following KA TKA were a combination of the alignment method and the implant design. Accordingly, our results might not translate to other designs such posterior stabilized designs, which are used widely.[36]

Related to the first key finding, the differences in the eight laxities from native after KA TKA were generally less than or comparable to those of the ACL-d knee. For example, the mean anterior laxity at 30° of flexion after KA TKA (5.1 ± 1.6 mm) was decreased relative to that of the ACL-d knee (6.7 ± 1.9 mm, $p < 0.0001$) (Fig. 6A). One possible design factor that contributes to decreased anterior laxity after KA TKA relative to that of the ACL-d knee is that the tibial insert is fixed on the tibia and quite rigid after TKA; in contrast, the native menisci (particularly the lateral meniscus) have freedom to move relative to the tibia and are deformable. Additionally, the articular surface of the tibial insert is more conforming than the menisci.[37] Hence, the increased conformity in conjunction with the rigidity of the conforming surface of the tibial insert might have helped to compensate for the large increase of 3.3 ± 1.6 mm in the anterior laxity when the ACL was transected.

The other four laxity-flexion angle combinations after KA TKA that were statistically different from those of the native knee (Figs. 5A and 7A) were either statistically different or trended toward being statistically different from those of the ACL-d knee, and the laxities of the ACL-d knee were not statistically different from those of the native knee. Thus, in contrast to the anterior laxity at 30° for which the replacement of the articular surfaces and menisci might have helped to compensate for the loss of the ACL, these four changes were likely caused by the replacement of the articular surfaces and menisci (Fig. 1). However, because the laxities were not statistically different at most of the flexion angles (Figs. 4A, 5A, 6A, and 7A), these results indicate that striving to restore the native joint lines and avoiding soft tissue releases is a promising approach to reduce the risk of differences in the laxities from native after TKA.

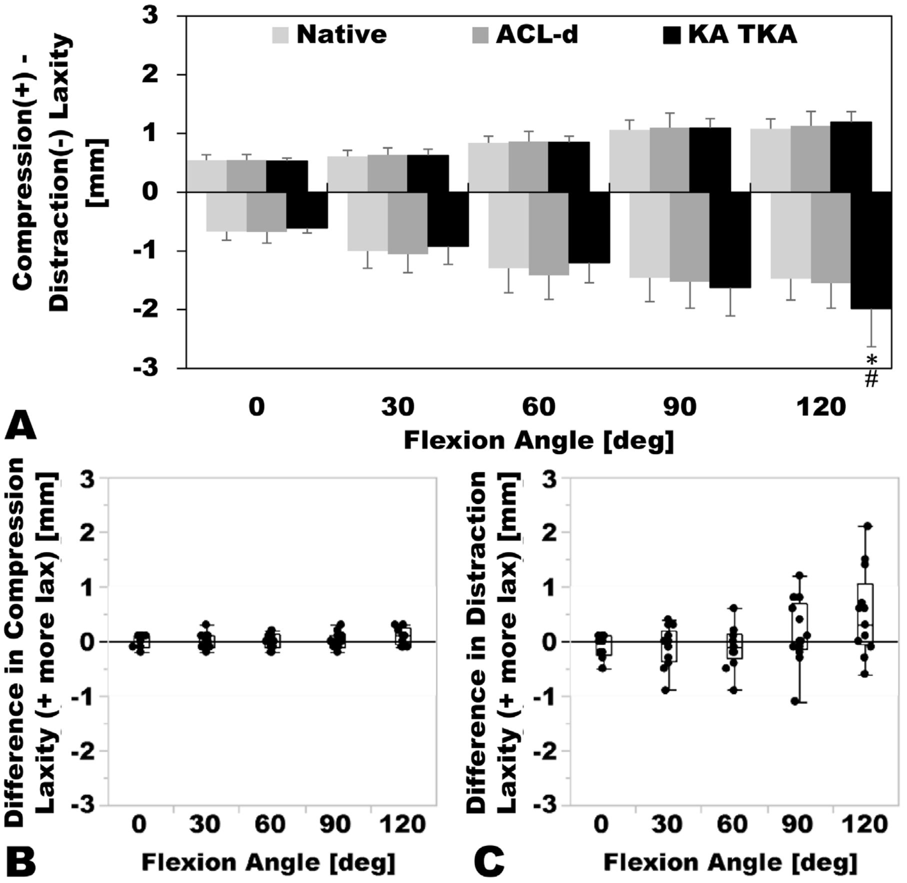

Figure 7. A vertical bar chart (A) shows the means (bars) and standard deviations (error bars) of the compression and distraction laxities of the native, ACL-d, and KA TKA knees. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the laxity after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the laxity of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots show the differences in the compression (B) and distraction (C) laxities after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

The differences in varus laxity and valgus laxity from native in mid-flexion (30°–60° of flexion) were less than 1.4° in all 13 KA TKAs and contradict a previous computational study that suggested patients after KA TKA may be susceptible to increased laxity in mid-flexion.[38] The mean V-V laxities after KA TKA measured in the present study were not statistically different from those in the native knee from 30° to 60° of flexion, which suggests that the soft tissue restraints after KA TKA were adequately tensioned to prevent increased laxity in mid-flexion (Fig. 3).

Related to the second key finding, the result that only 6 of 20 neutral positions were statistically different from native after KA TKA has several clinical

Table 1. Means, Standard Deviations, and p-Values for All Pairwise Comparisons Between the Laxities of the Native Knee, ACL-d Knee, and KA TKA for the Five Laxity-Flexion Angle Combinations Where the Laxities After KA TKA Were Statistically Different From Those of the Native Knee

Laxity	Flexion Angle	Difference in Laxity Between KA TKA and Native (Mean ± Standard Deviation, p-Value)	Difference in Laxity Between KA TKA and ACL-d (Mean ± Standard Deviation, p-Value)	Difference in Laxity Between ACL-d and Native (Mean ± Standard Deviation, p-Value)
Internal rotation	30°	2.3° ± 2.6°, $p = 0.002$	2.1° ± 2.9°, $p = 0.004$	0.1° ± 0.5°, $p = 0.8$
	90°	2.4° ± 2.1°, $p = 0.001$	2.0° ± 2.3°, $p = 0.009$	0.5° ± 0.7°, $p = 0.5$
External rotation	30°	−4.0° ± 2.4°, $p < 0.0001$	−4.6° ± 2.6°, $p < 0.0001$	0.6° ± 1.0°, $p = 0.4$
Anterior translation	30°	1.6 ± 2.1 mm, $p < 0.0001$	−1.7 ± 2.1 mm, $p < 0.0001$	3.3 ± 1.6 mm, $p < 0.0001$
Distraction	120°	0.5 ± 0.8 mm, $p < 0.0001$	0.4 ± 0.8 mm, $p = 0.0004$	0.1 ± 0.1 mm, $p = 0.5$

The level of significance was $p < 0.003$ because of the Bonferroni correction. Positive differences indicate an increase in laxity.

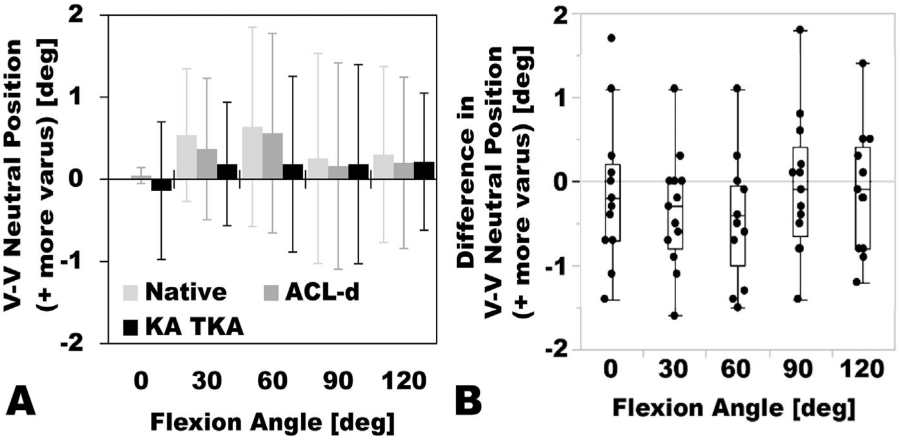

Figure 8. A vertical bar chart (A) shows the mean (bars) and standard deviation (error bars) of the varus-valgus (V-V) neutral positions of the tibia relative to the femur for the native, ACL-d, and KA TKA knees. The neutral positions were referenced to 0° of flexion in the native knee by computing the difference between the measured V-V neutral position and the V-V neutral position at 0° of flexion in the native knee. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the neutral position of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots (B) show the differences in the V-V neutral positions after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

implications. No statistical differences of the V-V neutral positions indicate that KA TKA likely achieved the goal of aligning the femoral and tibial components to restore the native joint lines and thus the native alignments of the limb and knee because malalignments would cause differences in the V-V neutral position.[39,40] No statistical differences of the C-D neutral position indicate that the correct tibial insert thickness was selected, and that the posterior tibial slope was correctly set using the intraoperative quality assurance checks.[28,30] While also affecting the laxities,[41,42] too thick or too thin of a tibial insert would have systematically affected the C-D neutral positions in distraction or compression, respectively, throughout flexion, and too little or too much posterior tibial slope would have affected the C-D neutral positions in distraction or compression, respectively, in flexion, but not in extension.

Although statistical differences in the A-P neutral position throughout flexion and in the I-E neutral position at 0° and 30° of flexion were observed (Figs. 9A and 10A), similarly large mean differences (4.4 mm more anterior at 10° of flexion and 8° more externally rotated at 30° of flexion[3,17]) have been reported in

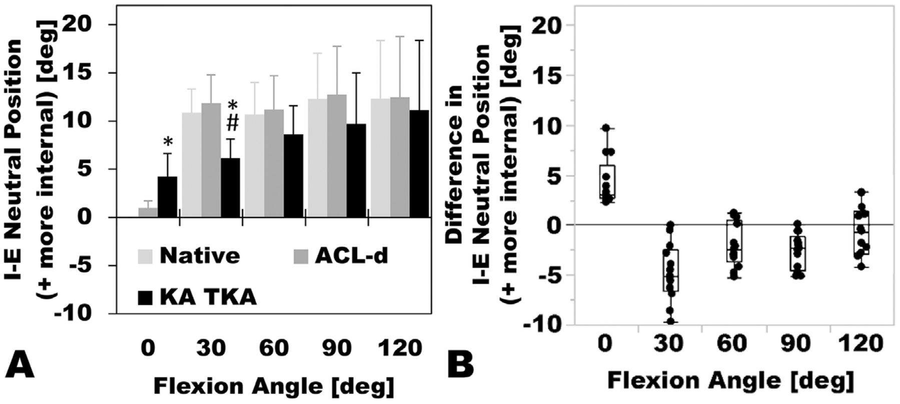

Figure 9. A vertical bar chart (A) shows the mean (bars) and standard deviation (error bars) of the internal–external (I-E) rotation neutral positions of the tibia relative to the femur for the native, ACL-d, and KA TKA knees. The neutral positions were referenced to 0° of flexion in the native knee by computing the difference between the measured I-E neutral position and the I-E neutral position at 0° of flexion in the native knee. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the neutral position of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots (B) show the differences in the I-E rotation laxities after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

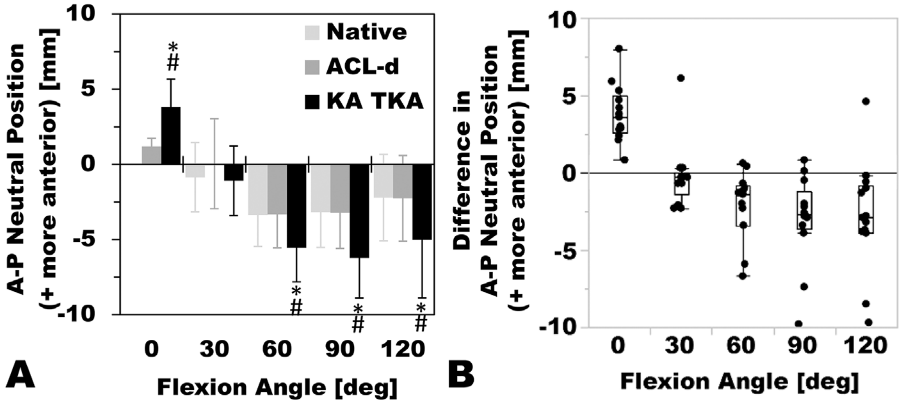

Figure 10. A vertical bar chart (A) shows the mean (bars) and standard deviation (error bars) of the anterior–posterior (A-P) neutral positions of the tibia relative to the femur for the native, ACL-d, and KA TKA knees. The neutral positions were referenced to 0° of flexion in the native knee by computing the difference between the measured A-P neutral position and the A-P neutral position at 0° of flexion in the native knee. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the neutral position of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots (B) show the differences in the A-P neutral positions relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

previous studies that used both different alignment goals (i.e., mechanical alignment) and different component designs. Therefore, these large mean differences are not specific to kinematic alignment of the particular components used in the present study. In fact, in all six of these I-E or A-P neutral position-flexion angle combinations that were statistically different after KA TKA from those of the native knee, each was also either statistically different or trended toward being statistically different than that of the ACL-d knee (Figs. 9 and 10). Because none of these neutral positions in the ACL-d knee were statistically different from those of the native knee, these six changes were likely caused by the replacement of the articular surfaces and menisci.

Achieving near native biomechanical function of the tibiofemoral joint is a multifactorial challenge. It is possible that a modified alignment of the components in conjunction with component design changes may cause smaller differences in the laxities and neutral positions from native than using the alignment method and component design in this study. For example, the A-P neutral position may be better restored by a less-conforming insert. However, reducing the conformity would likely increase the anterior laxity.[43–45] Hence, alterations to the posterior slope,

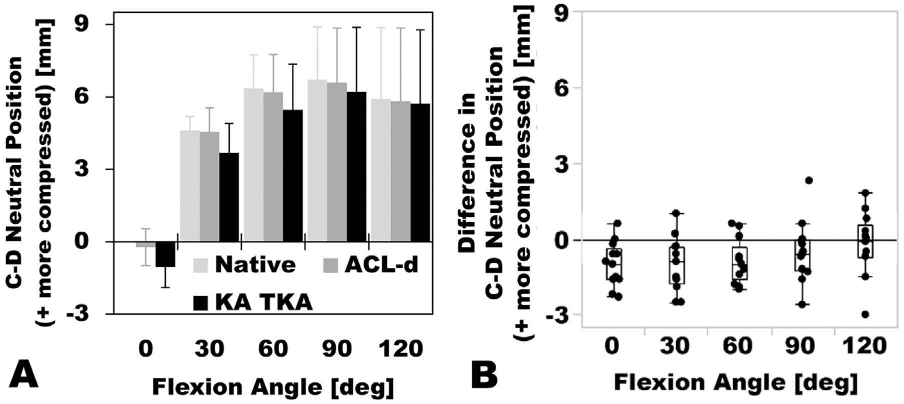

Figure 11. A vertical bar chart (A) shows the mean (bars) and standard deviation (error bars) of the compression-distraction (C-D) neutral positions of the tibia relative to the femur for the native, ACL-d, and KA TKA knees. The neutral positions were referenced to 0° of flexion in the native knee by computing the difference between the measured C-D neutral position and the C-D neutral position at 0° of flexion in the native knee. The results of the pairwise comparisons using the Bonferroni method at individual flexion angles are denoted by an asterisk (*) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the native knee, by a number sign (#) when the neutral position after KA TKA was statistically different ($p < 0.003$) from that of the ACL-d knee, and by a plus sign (+) when the neutral position of the ACL-d knee was statistically different ($p < 0.003$) from that of the native knee. Box-and-whisker plots (B) show the differences in the C-D neutral positions after KA TKA relative to those of the native knee. The top and bottom of each box represent the 75th and 25th percentiles, respectively; the horizontal line inside each box represents the median; the upper and lower whiskers of each box extend to the highest and lowest values (excluding outliers), respectively.

Table 2. Means, Standard Deviations, and p-Values for All Pairwise Comparisons Between the Neutral Positions of the Native Knee, ACL-d Knee, and KA TKA for the Six Neutral Position-Flexion Angle Combinations Where the Neutral Positions After KA TKA Were Statistically Different From Those of the Native Knee

Neutral Position	Flexion Angle	Difference in Neutral Position Between KA TKA and Native (Mean ± Standard Deviation, p-Value)	Difference in Neutral Position Between KA TKA and ACL-d (Mean ± Standard Deviation, p-Value)	Difference in Neutral Position Between ACL-d and Native (Mean ± Standard Deviation, p-Value)
Internal–External	0°	4.2° ± 2.3°, $p = 0.0003$	3.3° ± 2.3°, $p = 0.005$	1.0° ± 0.7°, $p = 0.4$
(+ more internal)	30°	−4.7° ± 2.9°, $p < 0.0001$	−5.7° ± 3.3°, $p < 0.0001$	1.0° ± 1.0°, $p = 0.4$
Anterior–Posterior	0°	3.8 ± 1.9 mm, $p < 0.0001$	2.6 ± 1.9 mm, $p = 0.0002$	1.2 ± 0.5 mm, $p = 0.08$
(+ more anterior)	60°	−2.2 ± 2.2 mm, $p = 0.002$	−2.2 ± 2.2 mm, $p = 0.002$	0.0 ± 0.5 mm, $p = 1.0$
	90°	−3.0 ± 2.8 mm, $p < 0.0001$	−3.0 ± 2.9 mm, $p < 0.0001$	−0.0 ± 0.4 mm, $p = 1.0$
	120°	−2.8 ± 3.6 mm; $p < 0.0001$	−2.8 ± 3.7 mm; $p < 0.0001$	−0.1 ± 0.5 mm, $p = 0.9$

The level of significance was $p < 0.003$ because of the Bonferroni correction.

which are associated with the A-P neutral position, posterior cruciate ligament tension, and flexion gap size,[46–48] in conjunction with changes in the conformity of the insert, may be necessary to achieve an A-P neutral position closer to native. Similarly, it may be possible to better limit differences in the laxities and neutral positions from native in the other degrees of freedom by optimizing component alignment and component design to more effectively compensate for loss of the ACL and menisci.

In conclusion, despite the two surgically induced changes, a minority of the mean laxity-flexion angle combinations (12.5% of 40) and mean neutral position-flexion angle combinations (30% of 20) were statistically different from native after KA TKA. These results indicate that the surgical goal of KA TKA (i.e., striving to restore the native joint lines and avoiding soft tissue releases) is a promising approach to achieve the outcome goal of biomechanical function that is not different from that of the native (i.e., pre-arthritic) knee after TKA. Modifications to the conformity of the components along with minor adjustments to the component alignment might enable surgeons to better achieve biomechanical function that is not different from that of the native knee.

AUTHORS' CONTRIBUTIONS

JDR: Research design; acquisition and interpretation of data; drafting, revision, and approval of manuscript. SMH: Research design; interpretation of data; revision and approval of manuscript. MLH: PI on grants which funded the study; research design; interpretation of data; revision and approval of manuscript.

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