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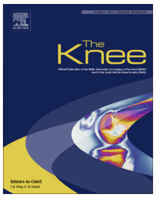

Insufficient lateral joint laxity after bicruciate-retaining total knee arthroplasty potentially influences kinematics during flexion: A biomechanical cadaveric study

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ABSTRACT

Background: Soft tissue balancing in bicruciate-retaining (BCR) total knee arthroplasty (TKA) is a challenge that must be overcome to achieve excellent clinical outcomes. However, the optimal degree of joint laxity has yet to be clarified. This cadaveric study sought to examine joint laxity after BCR TKA using a navigation system.

Methods: Knee joint laxity was quantified using an image-free navigation system in 8 intact fresh frozen cadavers under three conditions: the native knee, BCR TKA knee, and BCR TKA knee after anterior cruciate ligament resection. Rotational kinematics in the BCR TKA knee during flexion were compared according to whether joint laxity was increased or decreased.

Results: Knee joint laxity after BCR TKA under varus-valgus movement, anterior translation, and internal-external rotation loadings was similar to that of the native knee. However, lateral joint laxity was decreased during flexion in some cases. BCR TKA-treated knees with decreased lateral joint laxity at 90° of flexion demonstrated more limited tibial internal rotation in deep flexion than the native knee ($p < 0.05$). The loss of internal rotation in deep flexion was partly recovered by using a lateral insert with a posterior slope of +3°.

Conclusions: Restoring optimal joint laxity was not always straightforward in BCR TKA if the 4 ligaments were preserved. Lateral joint laxity was potentially decreased in BCR TKA and may result in kinematic conflict during flexion. Surgeons should be aware of the need to achieve sufficient lateral joint laxity in this type of BCR TKA.

Abbreviations: ACL, anterior cruciate ligament; TKA, total knee arthroplasty; CR, cruciate-retaining; BCR, bicruciate-retaining; PCL, posterior cruciate ligament; AP, anteroposterior; PS, posterior-stabilized; BKA, bi-compartmental knee arthroplasty; OA, osteoarthritis.

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1. Introduction

Sacrifice of the anterior cruciate ligament (ACL) is traditionally considered practical during total knee arthroplasty (TKA). However, the ACL is functional in a significant proportion of patients undergoing TKA [1,2]. It has been shown that resection of the ACL inevitably leads to significant changes in knee kinematics postoperatively and that replaced knees seem to behave more like ACL-deficient knees [3–5]. A recent report demonstrated that patients who underwent resection of an intact ACL at the time of cruciate-retaining (CR) TKA were less likely to be satisfied with the outcome [6]. Therefore, preserving both cruciate ligaments might allow better clinical outcomes by restoring function that is as close as possible to that of the normal knee. Bicruciate-retaining (BCR) TKA is a more recently reintroduced approach that can restore native knee kinematics and function. Two studies have shown that retention of the ACL achieves kinematics closer to those of the native knee [7,8]. Furthermore, favorable long-term outcomes of contemporary BCR TKA [9–11] indicate that this procedure holds promise. However, the clinical outcome of modern BCR TKA is controversial. While some studies have shown positive short-term results with the modern BCR implant [12–15], other reports raise concerns about a higher revision rate, stiffness, and loss of range of motion after BCR TKA [16–18]. Specifically, loss of the flexion angle is unacceptable because the preoperative range of motion is relatively good in cases of BCR TKA. One possible reason for loss of the flexion angle is an incorrect soft tissue balance after BCR TKA. Previous studies have reported that lateral joint laxity is correlated with postoperative tibial internal rotation and flexion angle [19,20]. Given these findings, it appears that lateral joint laxity in the knee might be insufficient after BCR TKA.

The aims of this cadaveric study were to examine joint laxity after BCR TKA using a navigation system and to evaluate the influence of resection of the ACL on joint laxity after BCR TKA. The hypothesis was that lateral joint laxity is decreased after BCR TKA and influences the tibiofemoral kinematics.

2. Material and methods

2.1. Subjects

The study protocol was approved by our institutional review board (approval number 2068). Cadaveric specimens were provided by our Clinical Anatomy Education and Research Center. Eight knees from intact fresh frozen cadavers stored at −20 °C were used. The specimens were from 5 males and 3 females with a median age of 76 (range, 69–96) years at the time of death, with no knee deformity, arthritic change, severe osteoporosis, or history of lower limb trauma or prior surgery. The ACL and posterior cruciate ligament (PCL) were not damaged or degenerated in any specimen. Whole-body computed tomography (CT) was undertaken prior to testing to assess the morphology of each specimen. All BCR TKA procedures (Vanguard XP, Zimmer Biomet, Warsaw, IN) were performed with a measured resection technique using an image-free navigation system (Stryker Navigation, Version 1.0; Stryker, Kalamazoo, MI). The thickness of the posterior femoral condyle of the femoral component is the same for the medial and lateral condyles. The tibial component has a symmetric design with independent, shallow-dished medial and lateral inserts.

2.2. Surgical procedure

An appropriately trained senior surgeon performed all the surgical procedures. The standard medial parapatellar approach was used for exposure. The minimum amount of soft tissue release was performed to enable bone resection. Registration in the navigation system was performed based on anatomic landmarks in accordance with the manufacturer's instructions.

The surgical procedure has been described in detail previously [21]. Briefly, with use of the navigation system, the distal femur was cut perpendicular to the mechanical axis in the coronal plane and at 3° of flexion in the sagittal plane. The posterior condylar angle on the preoperative CT scan was measured to confirm the rotation of the femoral component was parallel to the surgical epicondylar axis. Then, to confirm full extension of the knee, a trial femoral component was placed. The proximal tibia was then resected perpendicular to the mechanical axis in the coronal plane. The posterior slope of the tibia was set as the native posterior slope of the medial plateau in the sagittal plane. The tibial component was aligned to the axis from the medial border of the tibial tubercle to the middle of the PCL [22]. To each compartment in all knees, a shallow-dished polyethylene insert with a thickness of 9 mm was placed. A custom-made insert with a +3° slope that was designed to increase joint laxity in flexion was also applied to the lateral side only for decreased lateral laxity cases of BCR TKA knees. This posterior slope of the custom-made insert was decided to ensure sufficient lateral laxity within the range where the thickness of the insert can be mechanically secured. Finally, the ACL was then resected to evaluate the effect of ACL resection on joint laxity after BCR TKA in all knees.

2.3. Evaluation of intraoperative knee kinematics and joint laxity

After registration, knee joint laxity was quantified in the native knee using the navigation system. Joint laxity with maximum manual stress to the knee and no angular acceleration was evaluated by the navigation system in anterior translation (mm) at 0° and 90° of knee flexion, varus-valgus movement (degree) at 0°, 30°, 60°, and 90° of knee flexion, and internal-external rotation (degree) at 0°, 30°, 60°, and 90° of knee flexion. The anterior translation of the tibia at extension and 90° of flexion in the sagittal plane was evaluated by comparing the amount of movement from the tibial position measured in the kinematic analysis using the femoral and tibial centers registered in the navigation system. These points remained consistent even after BCR TKA, so they were not re-registered during the procedure [21]. Varus-valgus laxity was evaluated using the mechanical axis of the tibia and femur. Internal-external rotation laxity was evaluated using the line perpendicular to the tibial anteroposterior (AP) axis and surgical epicondylar axis [21]. The same examiner performed these laxity measurements twice for each knee until the navigation system displayed no further changes in maximum recorded translation or angles [21]. The average values were used.

Next, the femorotibial kinematics of the native knee during passive knee flexion were recorded using the navigation system. The protocol used has been described in detail previously [21]. Briefly, the same examiner performed kinematic analysis twice for each knee by. To passively flex the knee, the examiner held the heel in the open palm of one hand so that tibial rotation was unrestricted while the other hand provided support beside the knee. During flexion, the examiner took care to avoid intentional rotation of the knee. The relative rotation angle between the femur and tibia was assessed using the surgical epicondylar axis and a line perpendicular to the tibial AP axis. The angle of tibial rotation during passive knee motion was automatically recorded by the navigation system. While assessing the intraoperative kinematics and joint laxity, the patellofemoral joint was reduced and the medial parapatellar arthrotomy was temporarily closed with double stitches. After the trial components were assembled, the kinematics and joint laxity of the BCR TKA were assessed using the same methods as those used to evaluate the native knee. Finally, the kinematics and joint laxity after ACL resection were recorded using the same methods. Figure 1 summarizes the order of the analysis completed.

2.4. Statistical analysis

Test-retest reliability of the measurements was assessed using intra-class correlation coefficients. In accordance with a previous study [21], we used repeated measures one-way analysis of variance and then Tukey's multiple comparison test to compare differences in joint laxity between the native knee, BCR TKA knee, and BCR TKA knee after ACL resection. Differences in the internal rotation angle of the tibia at each knee flexion angle were compared between the native knee and the BCR TKA knee using the paired *t*-test. Significance was established at $p < 0.05$. All measurements are given as the mean ± standard error of the mean. GraphPad Prism 8 (GraphPad Software Inc., La Jolla, CA) was used to perform all statistical analyses. Cadaver availability and an a priori power analysis using G power 3.1 software determined the sample size: 6 specimens were indicated to be sufficient ($\alpha = 0.05$; power level = 0.8; effect size = 0.4).

3. Results

Reliability of the measurements was excellent (intra-class correlation coefficients were > 0.9 for anterior translation, varus-valgus laxity, and internal-external rotation laxity). Knee joint laxity under anterior translation and varus-valgus movement did not differ significantly between the native knee and the BCR TKA knee (Figures 2 and 3). Lateral joint laxity expressed by varus stress loading was slightly decreased in the BCR TKA knee compared with the native knee, but the difference was not significant. There was a significant increase in anterior and external rotation laxity at full extension (0° of knee flexion) in the BCR TKA knee after ACL resection (Figures 2 and 4b). Interestingly, varus laxity at 90° of flexion in the BCR TKA knee after ACL resection was significantly greater than that in native knee and BCR knee (Figure 3a).

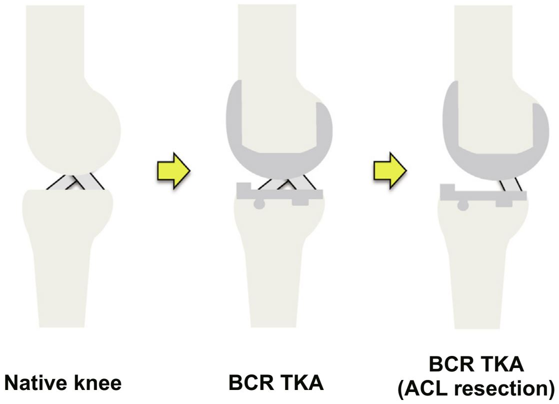

Figure 1. Sequence of laxity and kinematic evaluations made using the navigation system Analysis began with the native knee and was followed by BCR TKA and then BCR TKA after resection of the ACL. ACL, anterior cruciate ligament; BCR, bicruciate-retaining; TKA, total knee arthroplasty.

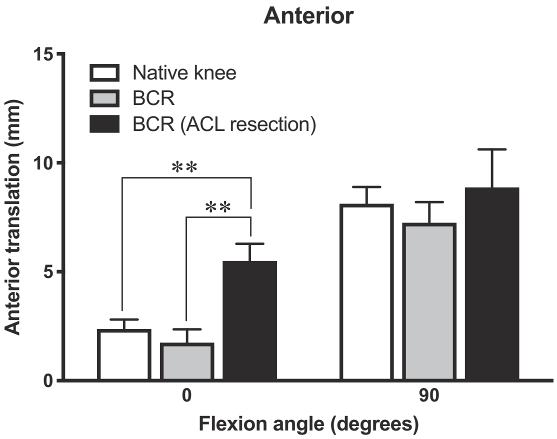

Figure 2. Comparison of anterior laxity at 0° and 90° of knee flexion between the three knee states. **$p < 0.01$. ACL, anterior cruciate ligament; BCR, bicruciate-retaining.

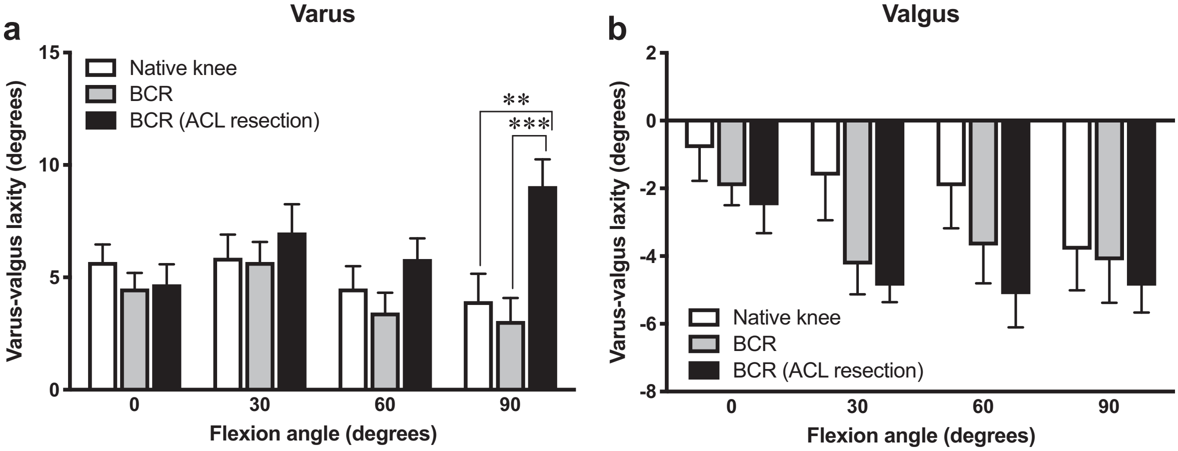

Figure 3. Varus-valgus laxity at 0°, 30°, 60°, and 90° of knee flexion between the three knee states. (a) Varus laxity. (b) Valgus laxity. The y-axis represents the varus angle of the mechanical axis. A positive value indicates varus laxity. **$p < 0.01$, ***$p < 0.001$. ACL, anterior cruciate ligament; BCR, bicruciate-retaining.

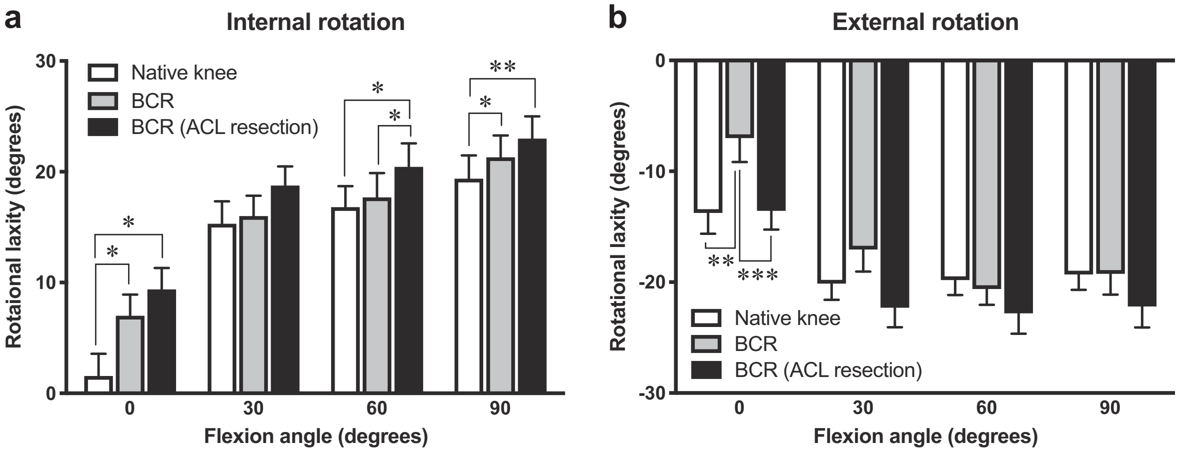

Figure 4. Internal-external rotation laxity at 0°, 30°, 60°, and 90° knee flexion between 3 knee states. (a) Internal rotation laxity. (b) External rotation laxity. The y-axis represents the femorotibial rotation laxity. A positive value indicates tibial internal rotation laxity. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$. ACL, anterior cruciate ligament; BCR, bicruciate-retaining.

Table 1
Comparison of varus laxity at 90° of knee flexion in each specimen.

Specimen	Laxity change		Group
	Native → BCR	Native → BCR (ACL resection)	
1	+5.0°	+11.0°	Laxity (+)
2	+1.5°	+6.5°	
3	+3.0°	+5.5°	
4	0°	+5.0°	
5	−3.5°	+6.0°	Laxity (−)
6	−3.0°	+4.0°	
7	−5.0°	+3.5°	
8	−5.5°	0°	

A positive value indicates varus laxity. ACL, anterior cruciate ligament; BCR, bicruciate-retaining.

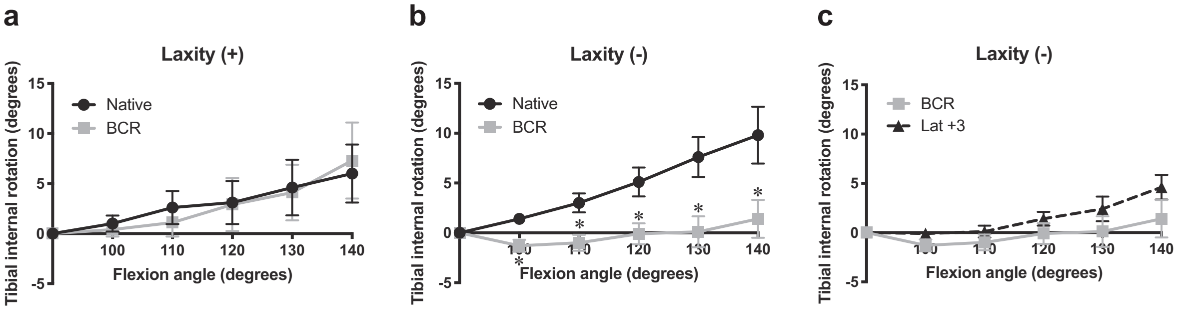

Figure 5. Relative tibial internal rotation angle (native knee, BCR TKA knee) from 90° flexion to maximum flexion. (a) Laxity (+) group. (b) Laxity (-) group. *$p < 0.05$. BCR, bicruciate-retaining; TKA, total knee arthroplasty.

According to previous studies [19,20], lateral joint laxity at 90° of knee flexion is correlated with postoperative tibial internal rotation and flexion angle. Furthermore, there was a significant difference in lateral joint laxity at only 90° of flexion in our study. Therefore, we compared lateral laxity at 90° of flexion in each specimen. Four BCR TKA knees (Table 1 Specimens 1–4) showed the same laxity or increased lateral laxity compared with the native knee, whereas the other 4 BCR TKA knees (Table 1 Specimens 5–8) showed decreased lateral laxity. These differences in change in laxity were then divided into two groups: lateral laxity (+) and lateral laxity (-) at 90° of flexion after BCR TKA. When comparing the tibial internal rotation angle of the BCR TKA knee from 90° to maximum flexion, the rotation pattern was similar in the lateral laxity (+) group and in the native knee (Figure 5a). In contrast, tibial internal rotation of the BCR TKA knee was significantly smaller in the lateral laxity (−) group than in the native knee (Figure 5b). Insufficient lateral joint laxity might result in loss of tibial internal rotation angle during flexion after BCR TKA. Interestingly, the loss of tibial internal rotation was partially recovered when using a lateral insert with a +3° slope in lateral laxity (−) group (Figure 5c).

4. Discussion

This study had two major findings. First, the tibial internal rotation angle after BCR TKA was decreased when lateral joint laxity at 90° of knee flexion was decreased. According to Matsuzaki et al. [19], lateral laxity at mid-to-deep knee flexion plays an important role in tibial internal rotation, and there is a positive correlation between tibial internal rotation in CR TKA and knee flexion postoperatively [19]. Moreover, Nakano et al. reported that lateral laxity at 90° of flexion in CR TKA plays an important role in the knee flexion angle postoperatively [20]. Therefore, insufficient lateral joint laxity might result in loss of flexion angle after BCR TKA. Interestingly, in decreased lateral laxity knees after BCR TKA, conversion to a lateral insert with a +3° slope that increases lateral joint laxity during flexion resulted in partial recovery of tibial internal rotation during flexion. This finding supports our hypothesis that sufficient lateral joint laxity during flexion is necessary to restore the native rotational kinematics after BCR TKA. Second, resection of the ACL significantly expanded lateral joint laxity at 90° of flexion. This finding indicates that lateral joint laxity at 90° of knee flexion in the BCR TKA knee is significantly smaller than that in a TKA knee in which the ACL is sacrificed. Thus, it is not always as easy to achieve sufficient lateral joint laxity during flexion in the BCR TKA knee as it is in the TKA knee where the ACL is sacrificed. If sufficient lateral laxity during flexion is not achieved in the BCR TKA knee, there is a risk of overstuffing and kinematic conflict in flexion.

To achieve good clinical outcomes after TKA, appropriate soft tissue balancing and accurate osteotomy and implantation must be ensured [23–25]. Aunan et al. recently reported that medial stability with relative lateral laxity is associated with good clinical results after TKA [26]. If we consider the effect of the ACL in varus laxity seen in the present study, medial stability with relative lateral laxity is easy to achieve in ACL-sacrificing TKA, such as posterior-stabilized (PS) or CR TKA; however, such soft tissue balancing is difficult to achieve in BCR TKA, especially at 90° of flexion. Furthermore, the thickness of the posterior femoral condyle bone resection also influences soft tissue balancing at 90° of flexion. Minoda et al. reported that the rotation center of the posterior reference guide affects the size of the femoral condyle [27]. When the central rotation type is used, as in the present study, the bone resection thickness in the posterior femoral condyle increases on the medial side but decreases on the lateral side with external rotation of the femoral component. Bone resection of a lateral posterior femoral condyle that is thinner than the posterior condyle of the femoral component results in a smaller lateral flexion joint gap [27], which might cause a limited flexion angle or pain in the posterolateral corner. Therefore, a femoral component design common to BCR and CR TKA could result in kinematic conflict during flexion in the BCR TKA knee if adequate lateral laxity at 90° of flexion is not achieved. To avoid overstuffing in the lateral compartment at 90° of flexion, the magnitude of external rotation and thickness of the lateral posterior condyle bone resection should be determined in order to achieve adequate lateral joint laxity, as long as it does not affect patellar tracking. On the other hand, Dennis et al reported paradoxical anterior femoral sliding motion, which means mid flexion instability occurs most frequently in CR TKAs [28]. Accordingly, excess joint laxity in BCR TKA is similar to an ACL dysfunctional or deficit knee and may lead to joint instability and paradoxical femorotibial anterior sliding. Therefore, excess joint laxity should also be avoided, and further studies are necessary to establish the optimum joint laxity in BCR TKA.

Our findings show that AP knee joint laxity is similar in the BCR TKA knee and the native knee, which is consistent with previous findings [7,8,12,29–32]. Halewood et al. reported that knee AP laxity was reduced more when a prototype BCR TKA procedure was used than when conventional CR TKA was performed, and no differences were found between the BCR TKA knee and the native knee in a cadaveric model [30]. Baumann et al. found that the static balance ability after BCR TKA was superior to that after conventional PS TKA [12]. Accordingly, BCR TKA appears to be a biomechanically attractive procedure and is anticipated to improve not only functional outcome, but also patient satisfaction.

Consistent with previous studies of ACL function in the native knee [33–36], in our study the BCR TKA knee after ACL resection showed a significant increase in anterior and external rotation laxity at full knee extension (knee flexion 0°). Lo et al. compared joint laxity between the native knee, the knee after bicruciate-retaining bi-compartmental knee arthroplasty (BKA), and the knee after CR TKA. Interestingly, joint stability was similar in the BKA knee and the native knee but was inferior in the CR TKA knee when compared with the native knee in the anterior, posterior, valgus, varus, and external rotation directions [31]. Their results also demonstrated that ACL resection significantly increased varus laxity in flexion. Although there was a difference in joint status between their study and ours, our finding that ACL resection increases lateral joint laxity during flexion is consistent.

This cadaveric study using whole specimens had the advantage of allowing easy comparison of preoperative and postoperative joint laxity and pre-resection and post-resection of the ACL in the same knee using a navigation system. Another advantage was that none of the knees were arthritic and had normal knee kinematics prior to the surgery.

This study has several limitations. First, intraoperative laxity was evaluated in normal cadaveric knees, and our data for normal knees may differ from those for knees with osteoarthritis (OA) because lateral joint laxity is considered to be greater in varus OA knees than in normal knees. Therefore, this issue should be investigated in navigation-assisted TKA for OA knees. Second, it is difficult to simulate muscle tension and weight-bearing conditions in a cadaveric study. An *in vivo* study is necessary to confirm our results. According to previous weight-bearing kinematic literature [8], patients with an ACL-retaining TKA had more natural tibiofemoral kinematics and stability than those with PCL-retaining TKA. Tsai et al. reported that BCR TKA does not restore native tibiofemoral articular contact kinematics during gait [37]. In our study, the knee joint stability after BCR TKA is similar to that of the native knee; however, sufficient lateral joint laxity during flexion is necessary to restore the native rotational kinematics after BCR TKA. Their results are consistent with our findings even in the weight-bearing condition. Third, bone cutting of the femur was performed with a measured resection technique using a central rotation type posterior reference guide. Modified gap techniques, other types of posterior reference guides, and other types of femoral components that might influence the outcome should be investigated in the future. Finally, the experimental procedure involved manual passive stress by the evaluator. However, our study, like a previous study [21], demonstrated reliable intra-rater intra-class correlation coefficients. Therefore, the measurements obtained in this study can be considered valid and reproducible.

To avoid overstuffing and kinematic conflict in this type of BCR TKA, surgeons should maintain adequate lateral joint laxity in flexion by considering the magnitude of external rotation of the femoral component and the depth and posterior slope of the tibial bone cut. Using a navigation system for intraoperative kinematic evaluation would be useful for detecting kinematic conflict during flexion, although this problem might be better solved ultimately with anatomic femoral component design, polyethylene inserts with variable posterior slopes, or robotic-assisted surgery that predicts the postoperative soft tissue balance before bone resection. Further clinical studies are necessary to establish the optimal joint laxity in the BCR TKA knee.

5. Conclusions

Restoring optimal joint laxity is not always straightforward in BCR TKA if the 4 ligaments are preserved. Lateral joint laxity was potentially decreased in the BCR TKA knee and may result in kinematic conflict during flexion. Surgeons should be aware of the need to achieve sufficient lateral joint laxity in this type of BCR TKA.

Ethical approval

All procedures performed were approved by the institutional review board of our hospital (approval number 2068) and done in accordance with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent

The cadaveric specimens were obtained from Clinical Anatomy Education and Research Center of our hospital. Specimens were from individuals who had consented in their lifetime to donate their body to education and research after death.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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