Original Article

In Vivo Kinematic Analysis of Bicruciate-Retaining Total Knee Arthroplasty Focused on Function of the Anterior Cruciate Ligament

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ABSTRACT

Introduction: The utility of a bi-cruciate retaining total knee arthroplasty (BCR-TKA) is uncertain. This study aims to examine whether there is a difference in the kinematics of BCR-TKA and cruciate-retaining total knee arthroplasty (CR-TKA) with a shearing force on the anterior cruciate ligament (ACL).

Methods: The subjects were 10 varus knees that underwent TKA (BCR: five knees, CR: five knees) at our hospital. We evaluated *in vivo* kinematics of the knee using fluoroscopy and investigated the femoral component translation relative to the tibial component from extension to maximum flexion, and the rotation angle between the components on level ground and a 10° forward slope.

Results: The femoral component showed gradual external rotation relative to the tibial component with flexion. In the BCR group, the rotation across the flexion angles was larger and the medial and lateral nearest points were positioned more anterior with a statistical significance under both conditions. The kinematic pathway showed a medial pivot pattern in which the lateral nearest point translated posteriorly, whereas the medial nearest point stayed until 90° flexion in the BCR group. Conversely, in 0°-20° flexion, the component rotated internally and it showed a medal pivot pattern until 20°-90° in the CR group.

Conclusions: There is a difference between the kinematics of BCR-TKA and CR-TKA. In the BCR group, kinematics close to screw home movement were found and these results provided evidence that conserved ACL function induced motion close to the normal knee, in comparison with CR-TKA.

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KEYWORDS: anterior cruciate ligament, bi-cruciate retaining total knee arthroplasty, kinematics

Introduction

Total knee arthroplasty (TKA) is an effective surgical procedure for pain and functional disorder caused by severe osteoarthritis of the knee and rheumatoid arthritis, but patient satisfaction remains at approximately 80%.[1–4] Conventional TKA does not reproduce normal knee joint movement because the anterior cruciate ligament (ACL)

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alone or both the ACL and posterior cruciate ligament (PCL) are resected, which reduces patient satisfaction. Bicruciate retaining total arthroplasty (BCR-TKA) preserving both the PCL and ACL was developed because it reproduces a more physiological knee joint movement compared with that reproduced by current cruciate-retaining TKA (CR-TKA) preserving only the PCL.

BCR-TKA is expected to reproduce physiological kinematics close to those of normal knees and to improve stability when compared with CR-TKA. It has been shown that *in vivo* kinematics after BCR-TKA are similar to those of the normal knee.[5] Nevertheless, there is no consistent view of the function or advantage of ACL retention via BCR-TKA, and various measures have been used to evaluate postoperative kinematics. In this study, kinematics after BCR-TKA and CR-TKA were analyzed using 2D-3D registration, with the hypothesis that BCR-TKA retaining the ACL is superior to CR-TKA for braking performance in the anteroposterior direction.

Regarding the function of the ACL, a comparison of reconstructed knees and the healthy side showed only weak stress on the ACL while walking on level ground, whereas measurements while walking on a downward slope were useful to detect differences in kinematics.[6] Walking on a downward slope has also been used to compare ACL-retaining unicompartmental knee arthroplasty and CR-TKA.[7] Thus, we compared the motion of deep flexion on level ground and on a 10° forward slope. This study aims to examine whether there is a difference in the kinematics of BCR-TKA and CR-TKA with a shearing force on the ACL. This is the first *in vivo* kinematic analysis of BCR-TKA on a forward slope.

Methods

Subjects

A total of 176 patients were treated with TKA performed by the same surgeon at our hospital between April 2016 and March 2018. Of these, 109 cases were excluded for the following reasons: rheumatoid arthritis of the knee, ACL tears, or suspected dysfunction on examination, severe varus knee with a preoperative femoral-tibial angle (FTA) of >190°, and a preoperative flexion angle of <90°. Of the remaining 67 cases, 38 knees (BCR: 13 knees, CR: 25 knees) were confirmed to be intact ACL on preoperative MRI and osteoarthritis of the knee of KL classification 3 or 4. Finally, 10 of these patients (10 knees; BCR: five patients (five knees), CR: five patients (five knees)) who could crouch from a standing position to deep flexion with a 6 month or longer course after surgery and consent to the study were included. Additionally, the advantages and disadvantages of BCR and CR were explained preoperatively to the above 38 patients, and the preferred model was selected. In the BCR group, a Vanguard XP® (Zimmer Biomet, Warsaw, IN, USA) was used in three males (three knees) and two females (two knees), and in the CR group, a Triathlon® (Stryker, Mahwah, NJ, USA) was used in two males (two knees) and two females (two knees). The anterior drawer test and Lachman test were negative in all cases. The preoperative FTA was 184.0° ± 2.3° in the BCR group and 184.4° ± 3.4° in the CR group, and the postoperative FTA was 176.8° ± 1.8° in the BCR group and 176.0° ± 2.5° in the CR group. The Knee Society Score (KSS 2019 version) was used to evaluate functional abilities.

The preoperative KSS was 47.4 ± 4.6 in the BCR group and 45.8 ± 3.1 in the CR group, and the postoperative KSS was 85.0 ± 2.7 in the BCR group and 83.8 ± 1.6 in the CR group. Surgery was performed with a medial parapatellar approach by the same surgeon in all cases. The ACL was macroscopically confirmed to be intact during surgery in all patients. Ages at the time of examination (mean ± standard deviation) were 74.2 ± 2.2 and 72.8 ± 4.3 years, and the postoperative follow-up periods were 17.6 ± 5.1 and 14.6 ± 5.8 months in the BCR and CR groups, respectively (Table 1). An explanation of the objectives of the study was given to the subjects before obtaining written consent, and the study protocol was approved by the Ethics Committee of the Faculty of Medicine, Toho University (No. A17041).

Imaging

Subjects practiced flexion motion several times, and then, the maximum flexion on level ground and a 10° forward slope were imaged via fluoroscopy to acquire lateral views (Fig. 1). Images of the knee joint during motion were acquired from the lateral direction at a speed of 12.5 frames/s using a fluoroscopic apparatus (Curevista®; Hitachi Medical Systems Ltd., Japan). The size of the acquisition and collection field of view was 17 × 17 inches, and the image size was 1,024 × 1,024 pixels. To prepare a 3D bone model for image matching, the full lengths of the bilateral lower limbs were imaged via CT before surgery, setting the slice interval at 1 mm. From the acquired CT data, 3D femoral and tibial models were prepared using 3D visualization and measurement software, Zed View™ (LEXI, Tokyo, Japan).

Table 1 Characteristics of patients

Item	BCR-TKA	CR-TKA	*P*-value *
Sex (male/female)	3:2	2:3	1.00 **
Age (y)	74.2 ± 2.2	72.8 ± 4.3	0.52
Height (cm)	158.7 ± 9.7	155.8 ± 7.0	0.68
Body weight (kg)	66.7 ± 9.4	56.6 ± 5.4	0.12
Body mass index (kg/m^2)	26.4 ± 1.8	23.3 ± 1.0	<0.05
Follow-up (months)	17.6 ± 5.1	14.6 ± 5.8	0.46
Preoperative FTA (°)	184 ± 2.3	184.4 ± 3.4	0.67
Postoperative FTA (°)	176.8 ± 1.8	176 ± 2.5	0.67
Preoperative KSS	47.4 ± 4.6	45.8 ± 3.1	0.40
Postoperative KSS	85 ± 2.7	83.8 ± 1.6	0.40
Postoperative FA (°)	121.2 ± 3.3	125.0 ± 3.1	0.07
Postoperative EA (°)	5.4 ± 4.8	2.0 ± 3.5	0.19

Values are presented as a ratio or mean ± standard deviation
*Mann–Whitney U test **Fisher's exact test
BCR-TKA: bicruciate-retaining total knee arthroplasty, CR-TKA: cruciate-retaining total knee arthroplasty, FTA: femoral–tibial angle, KSS: Knee Society Score, FA: flexion angle, EA: extension angle

Fig. 1 Acquisition of fluoroscopic images of deep flexion (single deep lunges). a: On level ground. b: On a 10° forward slope. The subjects performed deep flexion while holding on to a handrail for safety.

Analysis

Fluoroscopic images were analyzed with an image analysis program, Knee Motion™ (LEXI, Tokyo, Japan), using 2D-3D image matching. X-rays images were acquired from the hip to ankle joint in the standing position after surgery from two directions: the front and a 60° oblique angle; 3D coordinates were prepared from these images. Three 3D images were prepared by matching projected images of the bone model with the 3D shape prepared from preoperative CT images with the X-ray images in the two directions.[8] Then, the 3D models of the femoral and tibial components were read and similarly matched. The 3D model prepared using Knee Motion™ was matched with the fluoroscopic images and the positional relationship between the components was determined (Fig. 2). The estimated accuracy of relative motion between the metal components was ≤0.4° for rotation and ≤0.8 mm for translation.[9]

Evaluation method

Rotation kinematics were evaluated on the basis of the rotation angle of the femoral component relative to the tibial component. The angle was defined relative to the angle between the femoral and tibial axes, which was taken to be 0° (flexion angle 0°) to correct for variation due to the implant installation angle. Knee rotations were described using the joint rotational convention of Grood and Suntay.[10] External rotation of the femoral component was defined as positive and internal rotation as negative. Antero-

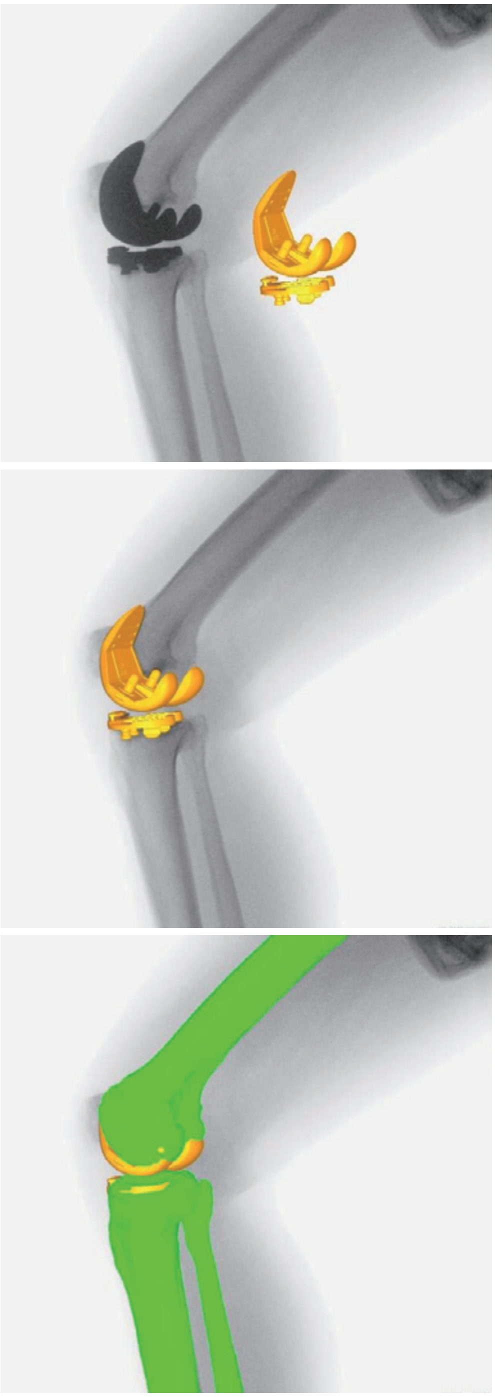


Fig. 2 2D/3D registration during a single deep lunge

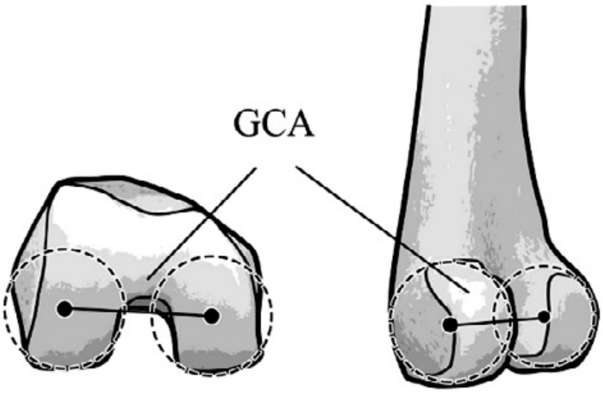


Fig. 3 Parameters of kinematic evaluation of the knee. The femoral GCA was projected on the tibial axial plane, and the medial and lateral endpoints of the GCA were evaluated on the basis of the tibial coordinate value.

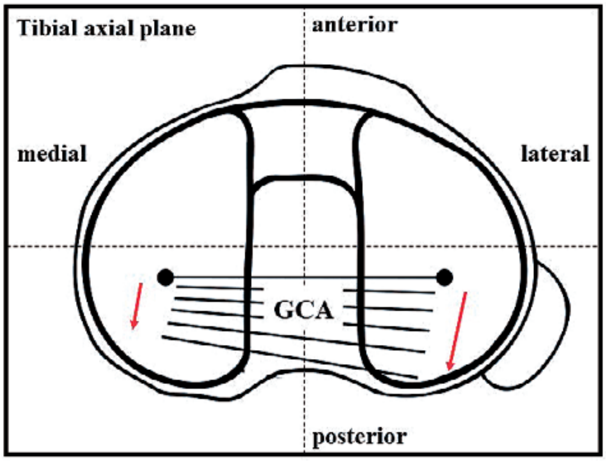
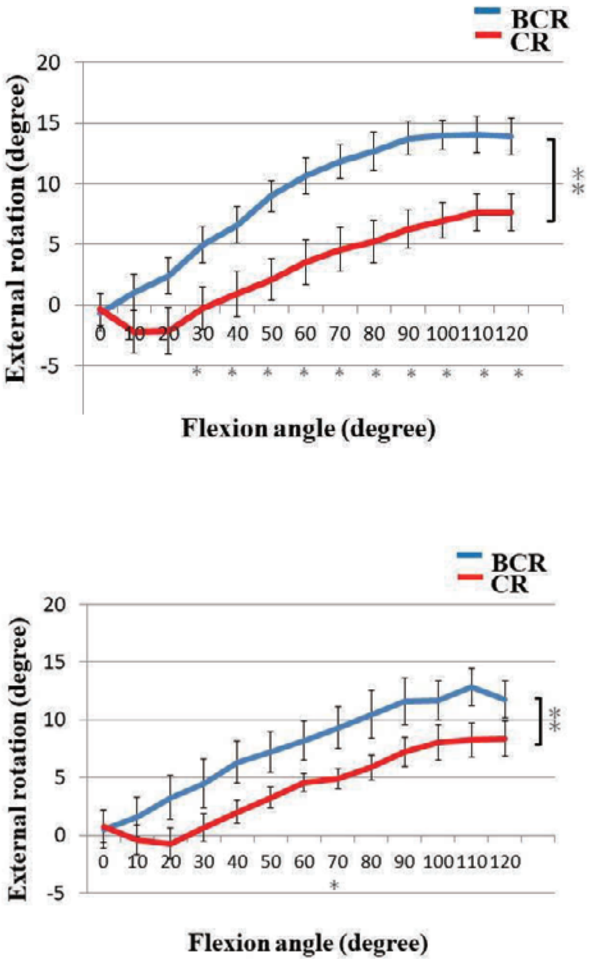


Fig. 4 Definition of the geometric center axis (GCA), as a line connecting the approximately spherical medial and lateral posterior condyles of the femur.

posterior translation and kinematics were evaluated at the point where the medial and lateral nearest points of the geometric center axis (GCA) were projected (the most distal point of the femoral component). Posterior translation from the tibial axis was defined as positive and anterior translation as negative (Fig. 3). The GCA is a line that approximately connects the spherical medial and lateral posterior condyles of the femur (Fig. 4).

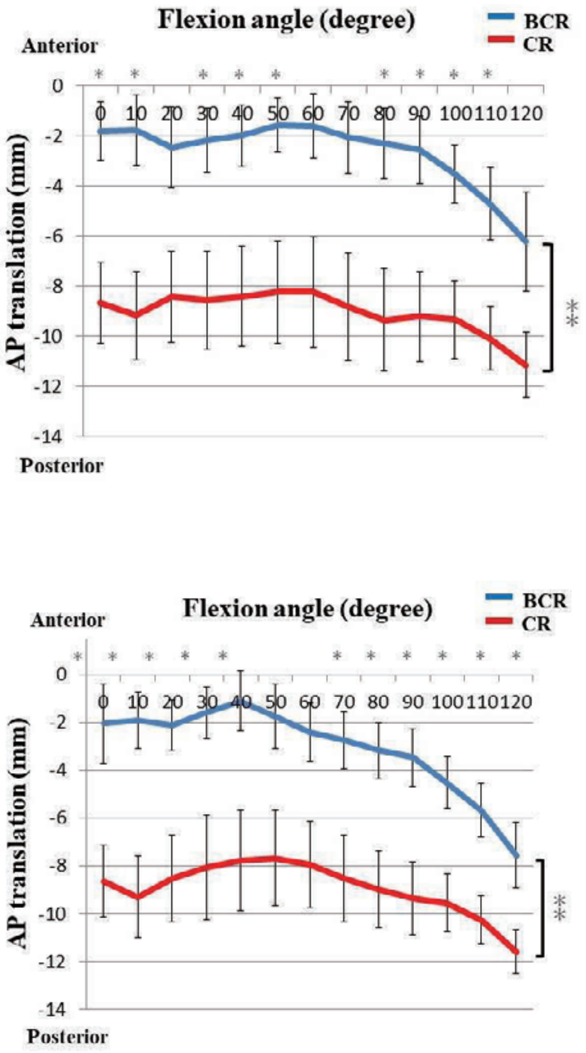
Statistical analysis was conducted using the Mann-Whitney U test to compare the characteristics of patients, the rotational angle, the location of lateral, and medial nearest points per flexion angle between the BCR group and the CR group. Fisher's exact test was used to compare sex (Table 1). Differences in these parameters between the BCR and CR groups across the flexion angles were compared by the Friedman test; $p < 0.05$ was considered to be statistically significant. Stata ver. 15 (Stata Corp., College Station, TX, USA) was used for all analyses.



a

b

Fig. 5 Rotation angle of the femoral component with deep flexion. $*p<0.05$ via the Mann–Whitney U test for the difference between BCR-TKA and CR-TKA per flexion angle. $**p<0.05$ via the Friedman test for the difference between BCR-TKA and CR-TKA across the flexion angles. a. On level ground. b. On a 10° forward slope.



a.

b.

Fig. 6 Anteroposterior (AP) translation of the medial contact point of the femoral component with deep flexion. $*p<0.05$ via the Mann–Whitney U test for the difference between BCR-TKA and CR-TKA per flexion angle. $**p<0.05$ via the Friedman test for the difference between BCR-TKA and CR-TKA across the flexion angles. a. On level ground. b. On a 10° forward slope.

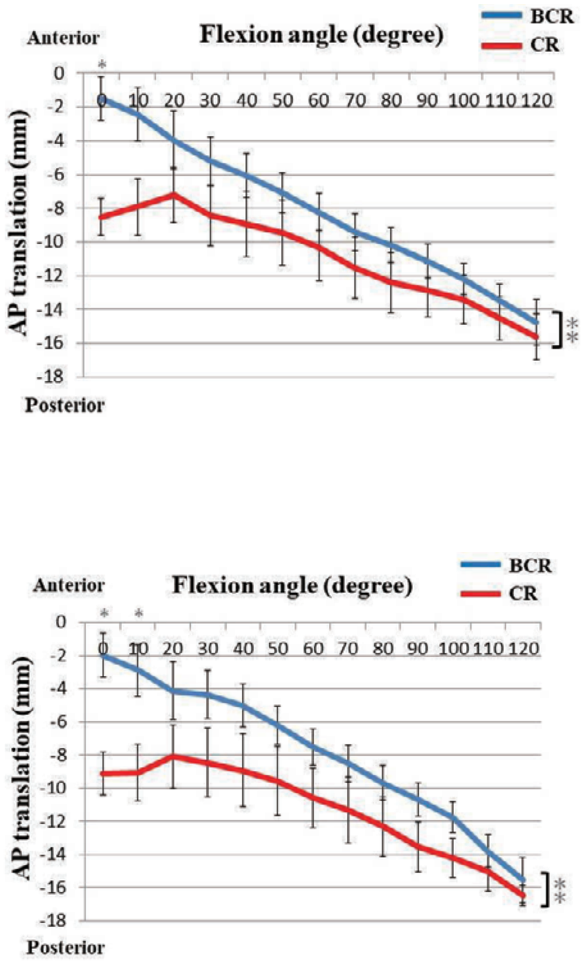
Results

On level ground

The mean flexion angles were 121.2° ± 3.3° and 125.0° ± 3.1°, and the mean extension angles were 5.4° ± 4.8° and 2.0° ± 3.5° in the BCR and CR groups, respectively. The femoral component showed gradually external rotation relative to the tibial component with flexion on level ground and on a 10° forward slope. On level ground, the external rotation at maximum flexion was 14.5° ± 1.9° in the BCR group and 7.9° ± 0.4° in the CR group (Fig. 5a). Using the Friedman test, the rotation across the flexion angles was larger in the BCR group with a statistical significance ($p < 0.001$). In flexion from 0° to 120°, the medial and lateral nearest points at the distal end of the femoral component translated posteriorly by 4.1 ± 1.7 and 13.2 ± 1.6 mm in the BCR group and by 2.5 ± 1.6 and 7.1 ± 1.7 mm in the CR group. Over all flexion positions, the medial and lateral nearest points were positioned more anterior in the BCR group with a statistical significance ($p < 0.001$, $p = 0.0013$ using the Friedman test) (Figs. 6a, 7a).

On a forward slope

On a forward slope, in flexion from 0° to 120°, external rotation was 12.7° ± 1.5° in the BCR group and 7.6° ± 0.7° in the



a.

b.

Fig. 7 Anteroposterior (AP) translation of the lateral contact point of the femoral component in deep flexion. *$p<0.05$ via the Mann–Whitney U test for the difference between BCR-TKA and CR-TKA per flexion angle. **$p<0.05$ via the Friedman test for the difference between BCR-TKA and CR-TKA across the flexion angles. a. On level ground. b. On a 10° forward slope.

CR group, and over all flexion positions the rotation angle was larger in the BCR group with a statistical significance ($p < 0.001$ via the Friedman test) (Fig. 5b). In flexion from 0° to 120°, the medial and lateral nearest points at the distal end of the femoral component translated posteriorly by 5.9 ± 1.8 and 13.6 ± 1.8 mm in the BCR group and by 2.9 ± 0.8 and 7.4 ± 0.9 mm in the CR group. Over all flexion positions, the medial and lateral nearest points were positioned statistically significantly more anterior in the BCR group ($p < 0.001$ via the Friedman test) (Figs. 6b, 7b).

Kinematic pathway

In detailed kinematic data by flexion position, the BCR group on the level ground had 14.3° of external rotation at 0°-90° flexion, whereas the CR group had an internal rotation at 0°-20° flexion and then 8° of external rotation until 110° (Fig. 5a). The medial nearest point was posterior 2 mm at 0°-90° flexion in the BCR group, but posterior 8.6 mm in the CR group over this flexion and translated further posterior as flexion angle increased (Fig. 6a). The lateral nearest point translated posteriorly 12.5 mm at 0°-120° flexion in the BCR group, but translated anteriorly 1.4 mm and posteriorly 8.5 mm in the CR group (Fig. 7a). The kinematic pathway showed a medial pivot pattern in which the lateral nearest point translated posteriorly while the medial nearest point stayed until 90° flexion in the BCR group. By contrast, the femoral component rotated slightly internally until 20° flexion and then rotated externally; consequently, the lateral nearest point translated posteriorly in the CR group. On a forward slope, the BCR group had 11° of external rotation at 0°-90° flexion, whereas the CR group had an internal rotation at 0°-20° flexion (similar to ground level) and then 9° of external rotation until 100° flexion (Fig. 5b). The medial nearest point was located posteriorly 2 mm from the baseline at 0° flexion, translated anteriorly 1 mm at a low flexion position, and translated 3 mm posteriorly until 90° flexion in the BCR group. The medial nearest point was located posteriorly 8 mm from the baseline at 0° flexion, translated anteriorly 0.5 mm at a low flexion position, and translated 9 mm posteriorly until 90° flexion in the CR group (Fig. 6b). The lateral nearest point translated posteriorly 13.5 mm at 0°-120° flexion in the BCR group but translated anteriorly 1 mm on average and posteriorly 7.5 mm until 120° flexion in the CR group (Fig. 7b).

Discussion

The results of this study showed that external rotation was significantly larger and that the medial and lateral nearest points were located significantly more anterior in the BCR group. This shows that preserving the ACL made a difference in the kinematics of CR-TKA.

Screw home movement (SHM) causing steep external rotation of the femoral component has been shown in squat motion of normal knees in extension to mild flexion,[11–15] but this has generally been considered to be due to the ACL and joint surface shape. The lateral contact point at the extension position is moved backward in knees with ACL failure, which loses SHM when compared with that of normal knees and suggests that the ACL plays a major role in SHM.[16]

In an analysis of BCR-TKA using unfixed cadavers, Hamada et al. found that kinematics were close to those of normal knees in flexion motion without loading after replacing the femoral component but predominantly showed an internal position from the extension position to early flexion when the tibial component was replaced, which reduced the rotation.17) Arauz et al. performed *in vivo* kinematic analysis with loading in 29 knees treated with BCR-TKA, in which tibial rotation from extension to mild flexion was small and SHM was not reproduced. The medial pivot shift representing tibial internal rotation centered on the medial side was only 59%, which suggested that ACL preservation alone cannot reproduce the kinematics of normal knees and that reproduction of the joint surface shape is important.18)

In this study, deep flexion on a forward slope that stressed the ACL was analyzed, besides *in vivo* kinematic analysis of BCR-TKA and CR-TKA on ground level. Both groups showed a medial pivot pattern in which the lateral component point translated posteriorly with centering of the medial component, but the rotation angle differed significantly between the groups. In 0°-20° flexion, the component rotated internally in the CR group but externally in the BCR group. This may be because the femoral component at extension (0° flexion) was located more internally in the BCR group than in the CR group. Thus, these results provided evidence that conserved ACL function induced motion close to SHM of the normal knee. These results differ from those of previous studies because the kinematics near SHM were observed in a nonphysiological articular surface. Nonetheless, the rotation degree on ground level in the BCR group was significantly larger than that in the CR group but smaller than that of normal rotation19) and similar to that found by Kono et al.20) Hence, the nonphysiological form of the articular surface may have had an effect.

Both medial and lateral nearest points between components were located anterior at 0° flexion in the BCR group. Conventional CR-TKA produces the nearest point at an extension that is more posterior than the normal knee due to PCL tension. Additionally, there may be an imbalance at the intermediate flexion position and paradoxical motion in which the femoral component slides forward against the tibia due to flexion.21) The femur translates posterior as a normal knee bends. CR-TKA leads to lower anteroposterior braking and induces paradoxical forward motion; consequently, the polyethylene insert wears and the moment arm of the quadriceps femoris muscle is low.22, 23) Slight anterior translation was found in the CR group on a forward slope, which was a paradoxical motion leading to decreased posterior translation. Although a similar anterior translation was also observed in the BCR group, there was no decreased posterior translation. This was because the preserved ACL function made a contact point at extension near to that of the normal knee and no paradoxical motion occurred, leading to kinematics that were close to normal. Moreover, the medial nearest point was located anterior at extension in the BCR group; consequently, the component translated posterior in parallel with the lateral nearest point, showing bicondylar rollback.

Kinematics close to those of normal knees after BCR-TKA compared with those after CR-TKA have been reported5, 24, 25) but with no significant difference in clinical outcome.26–28) One study showed that the advantage of ACL preservation was balance perception consistent with a normal knee,29) and these results show the value of BCR-TKA. Note that we conducted *in vivo* kinematic analysis using Vanguard XP® in this study. Journey™ II XR (Smith & Nephew, Memphis, TN, USA), a newer device, reproduces the physiological form of the articular surface. Thus, it is expected to provide kinematics close to those of the normal knee and greater satisfaction for patients.

Limitations of the study

This study had several limitations. First, it included a small number of subjects and had low statistical power for the following reasons: there were few cases in which BCR-TKA was indicated for surgery; obtaining consent for the study was difficult because of radiation exposure, and data analysis was time-consuming. Also, a randomized controlled trial would have been preferable, but this was difficult because of clinical considerations. Adjustment for confounding variables also could not be performed in this exploratory study. Thus, a larger study is needed to confirm the results. Second, we investigated only the postoperative kinematics and not preoperative kinematics. Third, surgical procedures have an effect on kinematics, and different implant design makes it difficult to evaluate the function of the ACL alone. The Vanguard CR may have been a better choice for the CR-TKA model, but the Triathlon® was used because the surgeon was familiar with this product. Fourth, there are no criteria for assessing the degree of ACL degeneration, and further studies are needed in more subjects, including those before BCR-TKA. There is also a need to determine if statistically significant findings can be interpreted as clinically significant. Additionally, the follow-up period ranged from 6 months to 2 years, but kinematics may change over longer periods.

Conclusions

We conducted *in vivo* kinematic analysis of deep flexion motion on level ground and on a forward slope to stress the ACL. In the BCR group, rotation was larger and the medial and lateral nearest point was anterior when compared with those in the CR group under both conditions. These findings suggest kinematics that were close to those of the normal knee in the BCR group.

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Authors' contribution: HA and RT participated in data analysis and contributed as surgical assistants. YN participated in the statistical analysis. HT and TK participated in the design of this study and the revision of the article. All authors read and approved the final manuscript.

Ethics statement: This study protocol was approved by the Ethics Committee of the Faculty of Medicine, Toho University (No. A17041).

Conflicts of interest: None declared.

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