RESEARCH ARTICLE

Kinematics of bicruciate stabilized and cruciate retaining total knee arthroplasty

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Abstract

Few studies have been reported about kinematic comparison between bicruciate stabilized and cruciate retaining total knee arthroplasty with the same anatomical surface geometry. The aim of this study was to demonstrate the in vivo kinematics and postoperative patient-reported outcomes of these two surgeries with the same anatomical surface geometry. We analyzed 17 bicruciate stabilized and 18 cruciate retaining total knee arthroplasties using single-plane fluoroscopic surveillance with two- to three-dimensional registration techniques during squatting from minimum to maximum flexion. Flexion angle, femoral external rotation, anteroposterior position of the medial and lateral sides, and postoperative 2011 Knee Society Scores were analyzed. Maximum flexion angles were larger for bicruciate stabilized than for cruciate retaining total knee arthroplasties. There was no significant difference in femoral external rotation between the two types. The medial and lateral femoral condyles in bicruciate stabilized type translated more posteriorly during deeper flexion and at maximum flexion angle, respectively, than those in cruciate retaining total knee arthroplasty. Both groups revealed medial pivots in early flexion, but during deep flexion, bicruciate stabilized total knee arthroplasty revealed bicondylar roll-back and cruciate retaining total knee arthroplasty revealed paradoxical anterior motion. Both groups exhibited similar results in postoperative 2011 Knee Society Scores. Bicruciate stabilized and cruciate retaining total knee arthroplasties with the same anatomical articular surfaces demonstrated different kinematics patterns during squatting. However, there were no significant differences in postoperative 2011 Knee Society Scores between the two types of surgery.

KEYWORDS
bicruciate stabilized, cruciate retaining, kinematics, total knee arthroplasty

1 | INTRODUCTION

Normal knee kinematics are influenced by the cruciate ligaments and surface geometry of the tibial plateau and femoral condyle.[1] However, following total knee arthroplasty (TKA), the knees are also influenced by the surface geometry of the tibial insert and femoral component, and the preservation of the posterior cruciate ligament (PCL) in cruciate retaining (CR) TKA or the postcam mechanism in posterior stabilized (PS) TKA.[2–5] To replicate normal knee kinematics, the JOURNEY II BCS (Smith & Nephew) knee system was developed, and has been available in Japan since 2013. This system has an asymmetrical tibial insert, which is concave on the medial side and convex on the lateral side with a multiradius femoral component that mimics the normal femoral condyles. Bicruciate stabilized (BCS) TKA aims to substitute both cruciate ligaments using a dual postcam design. Several studies have reported that BCS TKA demonstrated natural in vivo kinematics during daily activities. Kono et al.[6] reported that BCS TKA showed mid-flexion stability and good clinical outcomes. Ishibashi et al.[5] have previously reported about the anteroposterior (AP) stability of BCS TKA in comparison with conventional PS TKA during squatting and ascending/descending stairs; these results indicated it was affected to some extent by the articular surface geometry.[5,6]

A previous report compared PS and CR TKAs with the same surface geometry from a kinematic point of view. PS TKA showed a greater femoral posterior roll-back and maximum flexion during step-up and lunge activities than CR TKA.[7] This was because CR TKA allowed less femoral posterior roll-back and more frequent paradoxical anterior motion than PS TKA, in which posterior impingement may occur and interfere with knee flexion.[8,9] These results were consistent with systematic reviews that have shown that the maximum flexion angle of PS TKA was significantly larger than that of CR TKA.[10,11]

Previous conventional TKA systems have had curved on curved articular surfaces on both medial and lateral sides. CR TKA with the same articular geometry as BCS TKA (JOURNEY II CR, Smith & Nephew) has been available in Japan since 2015. There are many factors that affects knee joint kinematics after TKA, such as gender, body mass index, and ligament balances. The articular surface geometry of femoral component and tibial insert is one of them.[2–5,12,13] However, there are no reports about in vivo kinematic comparisons between BCS and CR TKAs with the same anatomical surface geometry.

The purpose of this study was to compare the in vivo kinematics of BCS and CR TKAs that have the same anatomical articular surface. We hypothesized that BCS and CR TKAs with the same anatomical surface geometry should have similar kinematics. A detailed knowledge of kinematics would help in the planning of TKA and the selection of a prosthesis.

2 | METHODS

This was a retrospective observational study and it was conducted with institutional review board approval. The surgical indications for CR TKA at our institution were that preoperative flexion contracture of less than 20°

TABLE 1 Patient demographics

	BCS	CR	*p* value
Number	17	18	
Age (years)	70.8 ± 6.4	71.9 ± 11.3	0.508
Gender (male/female)	9/8	4/14	0.060
Height (cm)	160.1 ± 7.1	153.4 ± 7.3	0.011*
Weight (kg)	62.3 ± 8.4	60.6 ± 10.6	0.468
BMI (kg/m²)	24.5 ± 4.4	25.5 ± 4.4	0.468
Disease (OA/RA)	17/0	16/2	0.157
Preoperative flexion contracture (°)	9.7 ± 7.8	11.1 ± 5.0	0.377
Preoperative maximum flexion (°)	124.4 ± 13.8	124.4 ± 6.4	0.431
Follow-up period (mo)	9.5 ± 3.6	10.1 ± 4.1	0.596
Postoperative flexion contracture (°)	2.4 ± 5.3	3.3 ± 4.9	0.195
Postoperative maximum flexion (°)	128.2 ± 12.7	125.3 ± 12.4	0.471
Postoperative PTS angle (°)	3.0 ± 2.0	5.8 ± 2.9	0.004*

Note: Data are expressed as mean ± SD.

Abbreviations: BCS, bicruciate stabilized; BMI, body mass index; CR, cruciate retaining; OA, osteoarthritis; PTS, posterior tibial slope; RA, rheumatoid arthritis.

*$p < 0.05$; statistical significance.

and the PCL was intact on preoperative magnetic resonance imaging (MRI). The surgical indications for PS and BCS TKAs were that the absence of both cruciate ligaments on preoperative MRI, or preoperative flexion contracture of greater than or equal to 20°.

We routinely conducted postoperative fluoroscopic surveillance for the patients who could perform squats and climbing stairs more than 6 months after TKA. We analyzed 34 patients (35 knees) who underwent TKA (one female patient underwent staged bilateral CR TKAs with 1 year between them). They provided informed consent for participation in this study. Seventeen knees were implanted with BCS between 2013 and 2015; this data set has been previously published.[5] The remaining 18 knees were implanted with CR TKA (JOURNEY II CR, Smith & Nephew) between 2015 and 2018. The preoperative diagnoses were composed of 17 case of osteoarthritis (OA) of the knee in patients who underwent BCS TKA, and 15 cases of OA, and two cases of rheumatoid arthritis of the knee in those who received CR TKA. The patient demographics are listed in Table 1. Pre- and postoperative flexion contracture and maximum flexion angles were measured by goniometer. Follow-up was defined as the period from TKA to the fluoroscopic analysis. A senior author performed the TKA procedures using the medial para-patellar or mid-vastus approach with modified gap technique for BCS TKA,[5] and with the measured resection technique for CR TKA. The PCL was preserved using the bone block technique in CR TKA.[14] For the tibia, sagittal alignment was targeted to be within 3° of the postoperative posterior tibial slope (PTS) in BCS TKA, and to 7° of the postoperative PTS in CR TKA, as per the manufacturers' recommendations. The patella was resurfaced

in all cases, and all components were cemented. We defined the postoperative PTS angle as the angle between the tangent line of the tibial baseplate and the line perpendicular to the proximal tibial anatomic axis (Table 2).

2.1 | Outcome measures

Single-plane fluoroscopic surveillance was used to measure weight-bearing deep knee bend (double-leg squats) as per a previously published paper (Figure 1).[15] Each patient was instructed to perform

TABLE 2 Kinematic variables during squatting

	BCS (N = 17)	CR (N = 18)	p value
Minimum flexion angle (°)	−2.1 ± 7.0	−4.2 ± 7.7	0.270
Maximum flexion angle (°)	122.0 ± 7.7	102.1 ± 14.9	<0.001*
Femoral ER angle at minimum flexion (°)	5.6 ± 4.5	4.7 ± 4.6	0.361
Femoral ER angle at maximum flexion (°)	12.4 ± 5.3	11.2 ± 5.3	0.593
Roll-back/forward			
Medial side (%)	12.0 ± 5.1	−6.1 ± 6.7	<0.001*
Lateral side (%)	28.8 ± 11.4	11.3 ± 8.4	<0.001*

Note: Data are expressed as mean ± SD. Roll-back was defined as the amount of anteroposterior translation from minimum to maximum flexion angles. Roll-back/forward were denoted as positive/negative.

Abbreviations: BCS, bicruciate stabilized; CR, cruciate retaining; ER, external rotation.

*$p < 0.05$; statistical significance.

squats, that is, the motion from extension to maximum flexion. The sequential motions were recorded as digital X-ray images (1024 × 1024 × 12 bits/pixel, 7.5-Hz serial spot images), and as a DICOM files using a 17-inch flat panel detector system (Ultimax-i DREX-U180; Toshiba Medical Systems). To estimate the spatial position and orientation of the component, a two- to three-dimensional (2D/3D) registration technique was used.[16,17] This technique was based on a contour-based registration algorithm using single-plane fluoroscopic images and 3D computer-aided design (CAD) models. The estimated accuracy of the relative motion between metal components was less than or equal to 0.5° in rotation and less than or equal to 0.4 mm in translation.[16,17] In the femoral coordinate system, the origin was defined as the center of gravity for the component. In the tibial coordinate system, the origin was defined as the center of the tibial tray surface. We evaluated the flexion angles between the femoral and tibial components, femoral external rotation (ER) angles relative to the tibial component, and the AP position of the medial (MAP) and lateral (LAP) sides. The flexion and femoral ER angles were described using the Grood and Suntay joint rotational convention.[18] The AP position was defined as the nearest point from the femoral component to the tibial axial plane and was shown as the percentage of tibial insert AP length in each tibial insert size. The origin was 0%, +50% on the anterior edge, and −50% on the posterior edge.[5] The 2011 Knee Society Scoring system score (KSS) was recorded postoperatively at the analysis.[19] All the values were expressed as mean ± SD.

2.2 | Statistical analysis

Statistical analysis was performed using JMP 13 (SAS Institute Inc.). The Wilcoxon rank sum test and Pearson's χ^2 test were used for
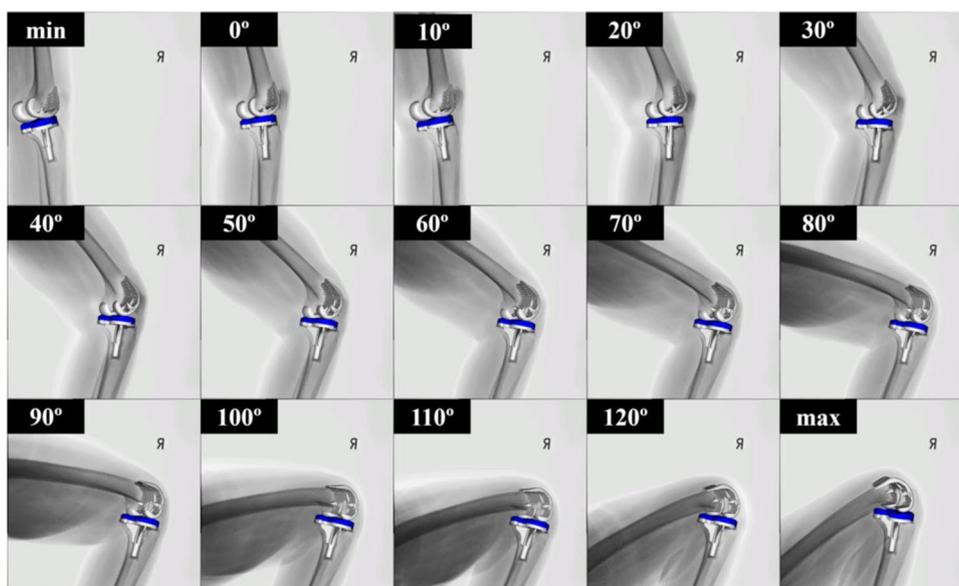

FIGURE 1 The two-/three-dimensional registration technique using single-plane fluoroscopic images during weight-bearing deep knee bending (squatting) motion from minimum to maximum flexion
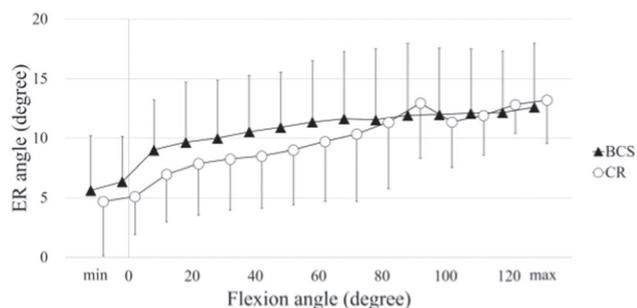
FIGURE 2 Femoral ER angle. There was no significant difference in the femoral ER angle between BCS and CR TKA during squatting. BCS, bicruciate stabilized; CR, cruciate retaining; ER, external rotation; TKA, total knee arthroplasty
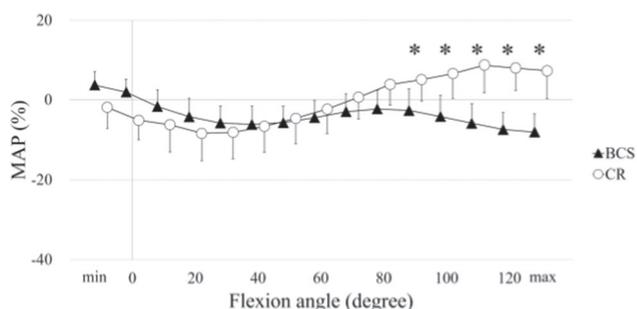

FIGURE 3 MAP. *Significant difference in the MAP between BCS and CR TKA ($p < 0.05$). BCS, bicruciate stabilized; CR, cruciate retaining; MAP, anteroposterior position of the medial; TKA, total knee arthroplasty
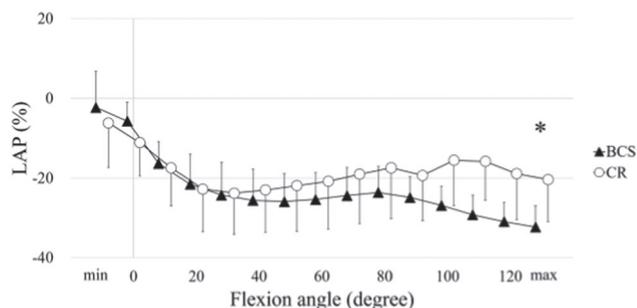

FIGURE 4 LAP. *Significant difference in the LAP between BCS and CR TKA ($p < 0.05$). BCS, bicruciate stabilized; CR, cruciate retaining; LAP, anteroposterior position of the lateral; TKA, total knee arthroplasty

comparisons of patient demographic data. The Wilcoxon rank sum test was also used to compare the flexion angle, and roll-back/forward. A two-way analysis of variance and post hoc pair-wise comparison (Tukey-Kramer test) were used to compare the femoral ER angle, and AP position. In consideration of the influence of the postoperative PTS on the AP position, linear regression analysis was performed. We also used linear regression analysis to detect the relationship between the roll-back and the maximum flexion angle. The Wilcoxon rank sum test

was used to compares the postoperative 2011 KSS between the two groups, and $p < 0.05$ were considered statistically significant. A power analysis showed that 17 knees in each group would allow detection of a difference of 5.0% ($\alpha = 0.05$, power = 0.8) with a *SD* of 5.0% in AP position between the two groups.

3 | RESULTS

3.1 | Flexion angle

During squatting, the ranges of motion (ROM) that meant the difference between the minimum and maximum flexion angle were 124.1° ± 13.4° in BCS TKA and 107.4° ± 16.4° in CR TKA ($p = 0.003$).

3.2 | Femoral external rotation angle

Both BCS and CR TKA rotated externally with flexion, and the femoral ER angles from minimum to maximum flexion were 6.2° ± 4.5° in BCS TKA and 6.5° ± 4.0° in CR TKA ($p = 0.856$, Figure 2).

3.3 | Anteroposterior position

The MAP at minimum flexion was 3.8% ± 3.4% in BCS TKA and −1.8% ± 5.3% in CR TKA ($p = 0.211$, Figure 3). The medial femoral condyle moved 9.9% ± 4.6% posteriorly from the minimum flexion to 40°, 3.9% ± 4.3% anteriorly from 40° to 80°, and then 5.5% ± 4.5% posteriorly from 80° to the maximum flexion in BCS TKA. In CR TKA, it moved 6.5% ± 3.8% posteriorly from the minimum flexion to 20°, 10.3% ± 8.3% anteriorly from 20° to 110°, and then 0.6% ± 1.8% posteriorly from 110° to the maximum flexion. The LAP at minimum flexion was −2.3% ± 9.1% in BCS TKA and −6.2% ± 11.1% in CR TKA ($p = 1.000$, Figure 4). The lateral femoral condyle in BCS TKA moved 23.7% ± 9.9% posteriorly from the minimum flexion to 50°, 2.3% ± 3.7% anteriorly from 50° to 80°, and then 7.9% ± 3.7% posteriorly from 80° to the maximum flexion. In CR TKA, the lateral femoral condyle moved 17.6% ± 7.1% posteriorly from the minimum flexion to 30°, 15.2% ± 12.8% anteriorly from 30° to 100°, and then 8.8% ± 11.6% posteriorly from 100° to the maximum flexion. The postoperative PTS negatively influenced the MAP at minimum flexion ($R = −0.55$, $p < 0.001$, Figure 5A). There was no correlation between the LAP at minimum flexion and postoperative PTS ($R = −0.14$, $p = 0.435$, Figure 5B). To summarize, BCS TKA revealed a medial pivot pattern from minimum flexion to 30°, a slightly femoral anterior motion from 40° to 80°, and bicondylar roll-back from 90° to maximum flexion (Figure 6). CR TKA revealed a medial pivot pattern from minimum flexion to 30° and femoral anterior motion from 30° to maximum flexion (Figure 6).

3.4 | Relationship between femoral roll-back and maximum flexion

For all 35 knees, linear regression detected a statistically significant correlation ($R = 0.63$, $p < 0.001$), with 9° of additional flexion for each additional 10% of roll-back (Figure 7).

3.5 | The 2011 Knee Society Score

The postoperative 2011 KSS are listed in Table 3. In BCS TKA, one patient moved after the fluoroscopic surveillance and the KSS questionnaire was not available. There were no significant differences in any categories for either BCS or CR TKAs.

4 | DISCUSSION

The most important finding of our study was that BCS and CR TKAs with the same anatomical surface geometry demonstrated different kinematics. This was observed especially at deep flexion angles in knees in which the PCL was functional. CR TKA did not demonstrate roll-back, but did show paradoxical anterior motion. Therefore, posterior impingement may occur and reduce the maximum flexion angle during weight-bearing conditions compared to BCS TKA. However, the 2011 KSS were similar between BCS and CR TKAs.

In the early flexion angles, there were no statistical differences in the AP positions of the medial and lateral sides between BCS and CR TKAs. In a previous study, Ishibashi et al. reported that the JOURNEY II BCS stayed in the medial sulcus at shallow flexion angles during stair motions and squatting.[5] The JOURNEY II CR also stayed in the medial sulcus; however, the medial femoral condyle shifted more posteriorly with a larger postoperative PTS at a minimum flexion angle. In this study, we analyzed the cases with 5.8° of the mean postoperative PTS in CR TKA. In cases with the postoperative PTS more than 6°, we could find differences in the AP positions. Fujito et al.[20] reported about the in vivo kinematics during squatting of a Japanese domestic CR TKA (FINE Total Knee System, Teijin Nakashima Medical), which has an asymmetrical

geometric tibial insert with high conformity at extension. In contrast to our observations, these authors found no significant differences in the AP positions of the medial and lateral sides between postoperative PTS ≤ 7° and ≥8°. These results suggest that the AP positions at early flexion angles were influenced by the conformity to the postoperative PTS. To achieve the optimal anterior positioning of the femur at extension, we should not make the postoperative PTS more than 6° when using the JOURNEY II CR.

During mid-flexion angles, there were no significant differences in the MAP and LAP between BCS and CR TKAs. In this part of the study, we did not observe the participation of both anterior and posterior postcam mechanisms. Therefore, the articular surface geometry directly affected the AP positions. The JOURNEY I Systems have a multiradius femoral component and relatively higher conformity between the femoral component and the tibial insert. Luyckx et al.[21] reported the higher conformity forces the femur to rotate excessively, resulting in postoperative knee pain and iliotibial band friction syndrome. Grieco et al.[22] reported that the JOURNEY II System was modified to have lower conformity, which affected the in vivo kinematics. Zambianchi et al.[23] reported that the medial femoral condyle of the JOURNEY II BCS was positioned more anteriorly compared to that of the JOURNEY I BCS at the mid-flexion angle during chair rising and stair climbing. The results were similar in the current study, and both BCS and CR TKAs using the JOURNEY II demonstrated anterior femoral positioning in the mid-flexion angle during squatting. This prosthesis had a multiradius femoral component that mimicked healthy femoral condyles. The radius was drastically decreased at 30°–40°, as shown by the manufacturer. Clary et al.[24] reported that the cause of the paradoxical anterior motion was a sudden reduction in the radius of curvature of the femoral component as well as lower conformity. Thus, the radius changes at 30°–40° mainly affected the femoral anterior motion, with reduced conformity in this range of motion.

For deeper flexion angles, bicondylar roll-back was observed in all cases of BCS-TKA. Ishibashi et al.[5] previously reported this was because posterior postcam engagement functioned from 77.2° ± 9.1°. On the other hand, CR TKA continuously revealed paradoxical anterior motion from mid-flexion. Dennis et al.[25] reported another reason for the paradoxical anterior motion could be the lack of the PCL function. We
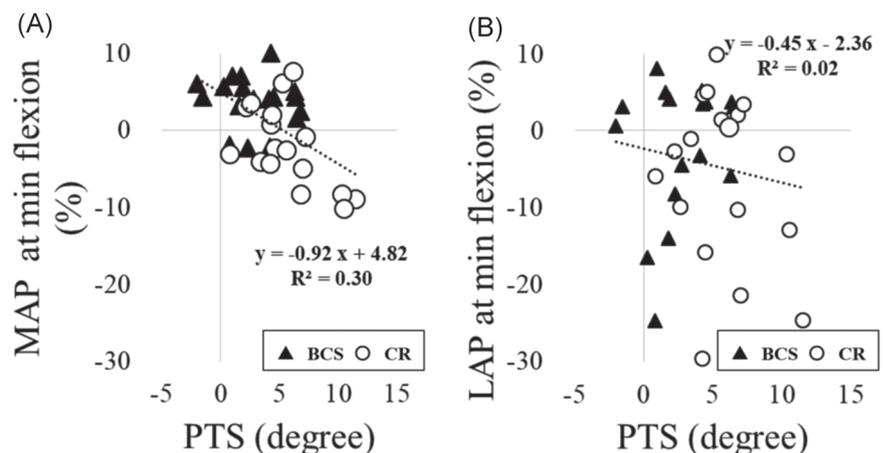

FIGURE 5 Correlation between MAP (A) and LAP (B) at the minimum flexion angle and postoperative PTS. LAP, anteroposterior position of the lateral side; MAP, anteroposterior of the medial side; PTS, posterior tibial slope
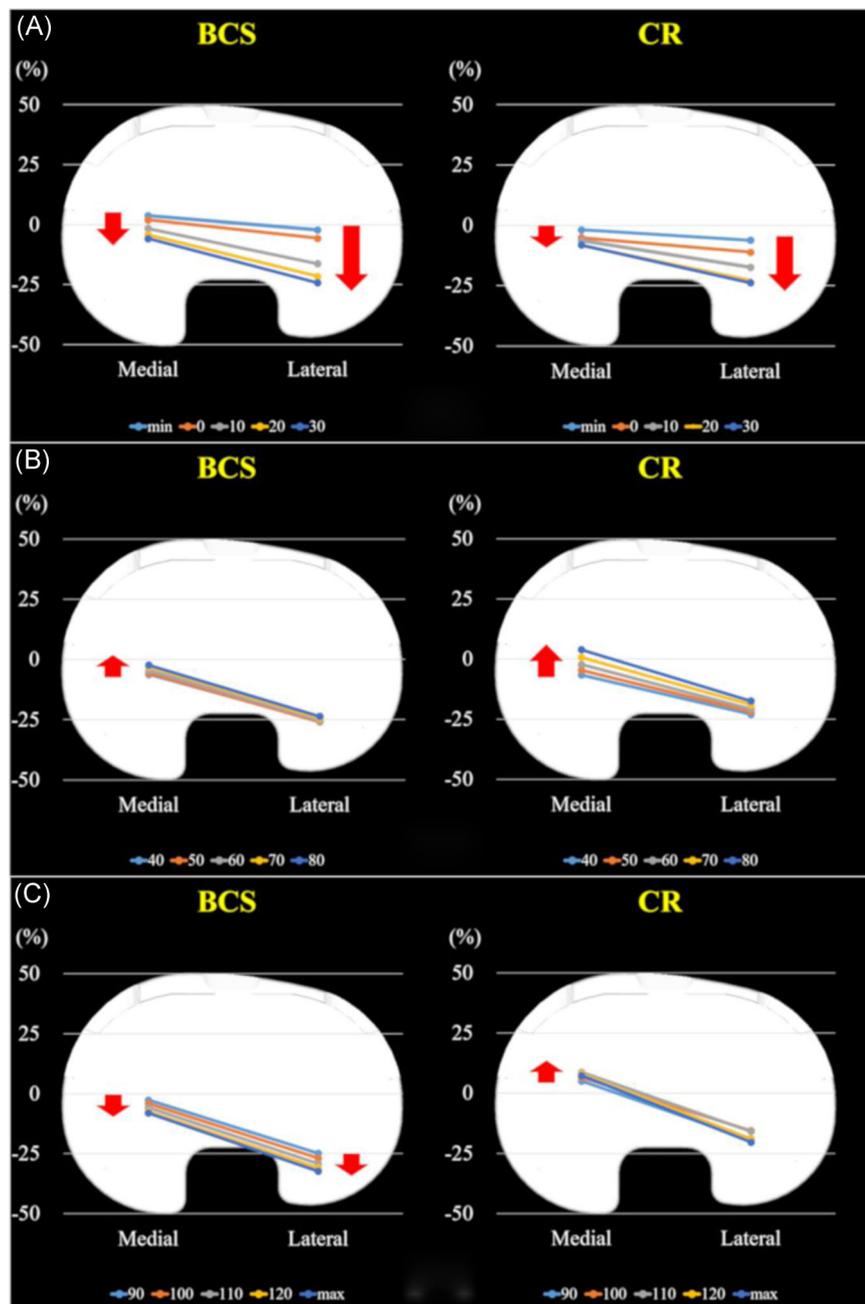
FIGURE 6 Kinematic pathway of BCS and CR TKA. Red arrows indicate the femoral motion relative to the tibial component. (A) During early flexion, medial pivot pattern was observed in both groups. (B) During mid-flexion, paradoxical anterior motion was observed slightly in BCS TKA and to a greater extent in CR TKA. (C) During deep flexion, BCS TKA exhibited bicondylar roll-back pattern and CR TKA continued to exhibit anterior motion. BCS, bicruciate stabilized; CR, cruciate retaining; TKA, total knee arthroplasty

previously reported that different prostheses for CR TKA revealed bicondylar roll-back using the same bone block technique for preserving the PCL.[20] Therefore, the PCL could not function even if it was preserved by a bone block technique using this prosthesis. Consequently, the intended roll-back for deep flexion angles was achieved in the use this prosthesis for BCS.

Regarding the flexion angle, no significant difference was observed in minimum flexion, but the maximum flexion and ROM were significantly larger in BCS than in CR TKA. Several meta-analyses have demonstrated that there were no significant differences in clinical scores between PS and CR TKAs, whereas the flexion of PS TKA was significantly larger than that of CR TKA.[10,11] In terms of kinematics, the posterior position of the femur on the tibia after TKAs was correlated with greater maximum flexion. This was because the posterior position of the femur could prevent early impingement between the femoral posterior cortex and the tibial insert.[8,9] The anatomical geometry of the articular surface would suggest normal kinematics, that is, medial pivot and bicondylar roll-back.[1] However, in this survey, CR TKA did not show proper roll-back and showed reduced maximum flexion (Figure 7). The result was similar with the conventional CR TKAs with non-anatomical surface geometry.[7,8] Upon physical examinations, there were no significant difference in the maximum flexion under nonweight bearing conditions as evaluated by goniometer (Table 1). Maximum flexion angle under weight bearing conditions was reduced compared to non-weight bearing conditions after TKAs because of the complexities involved with muscle force, soft tissue constraints, and geometric conformity.[26] Our
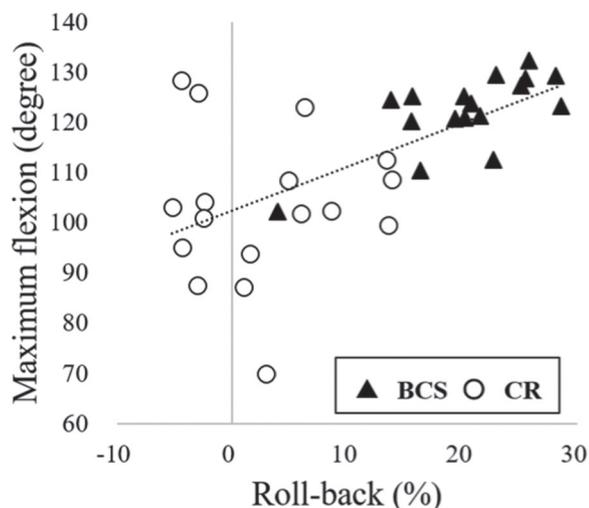
FIGURE 7 Correlation between roll-back and maximum flexion. Roll-back was defined as the amount of translation of the midpoint between medial and lateral sides from minimum to maximum flexion. Maximum flexion positively correlated with roll-back of the midpoint ($R = 0.63$, $p < 0.001$). BCS, bicruciate stabilized; CR, cruciate retaining

TABLE 3 Postoperative 2011 Knee Society Score

	BCS	CR	p value
Number	16/17	18/18	
Symptoms	19.7 ± 6.2	19.7 ± 4.9	0.848
Patient satisfaction	25.1 ± 9.8	29.7 ± 8.4	0.150
Patient expectations	8.4 ± 3.6	9.2 ± 3.3	0.468
Functional activities	21.4 ± 7.7	23.3 ± 7.1	0.420
Standard activities	23.9 ± 6.2	24.3 ± 4.5	0.890
Advanced activities	14.6 ± 6.2	13.9 ± 6.2	0.568
Discretionary knee activities	9.8 ± 4.8	11.4 ± 3.1	0.385
Total functional activities	69.6 ± 20.1	73.0 ± 17.9	0.796

Note: Data are expressed as mean ± SD.

Abbreviations: BCS, bicruciate stabilized; CR, cruciate retaining.

findings suggest that weight bearing conditions would be better than nonweight bearing conditions in evaluating the functional capabilities of different TKAs.

With regard to the femoral ER angles, there were no significant differences between each 10° interval and the amount of femoral ER from minimum to maximum flexion. In BCS TKA, medial pivot, slightly anterior motion, and bicondylar roll-back revealed femoral ER, whereas in CR TKA, femoral ER was indicated by medial pivot and paradoxical anterior motion. In summary, both BCS and CR TKAs revealed different kinematics but the same axial rotation patterns. Therefore, it may be important for the femur to rotate externally with cruciate ligaments or with substitution during deep knee bending motions.

Postoperative satisfaction after TKA was relatively lower compared to THA in previous studies.[27,28] Considering the relationship between the kinematics and patient satisfaction, implants are often designed to use medial pivot pattern and bicondylar roll-back. Nishio et al.[29] reported that an intraoperative medial pivot pattern revealed a better satisfaction score than a nonmedial pivot pattern. In the current study, BCS TKA showed nearly physiological kinematics, which consisted of a medial pivot and a bicondylar roll-back pattern. On the other hand, CR TKA showed abnormal kinematics, which consisted of a medial pivot and a paradoxical anterior motion pattern. However, in all categories of the postoperative 2011 KSS, including the satisfaction score, there were no significant differences. Patient-Reported outcomes (PROs) are affected by several factors, including kinematics, muscle strength, and preoperative conditions. Thus, abnormal kinematics do not always reduce the PRO.

This study has several potential limitations. First, it was not a randomized trial, and it included selection bias for the surgical allocation of patients into BCS or CR TKA groups. This resulted in different gender/height distribution and target postoperative PTSs among the groups. In addition, not all cases after TKA were able to be included in this study because some patients could not give consent to this study, and some patients were unable to perform squatting and climbing stairs. Second, the fluoroscopic surveillance was done only for the squatting motion. PRO could be affected by several daily activities. However, the squatting motion is considered to be a full weight bearing motion and uses a wide range of knee motions. Therefore, squatting is one of the key ways to conduct kinematic surveillance. In a future study, we plan to analyze the other motions. Third, this study was for short-term evaluations of approximately one year and we considered only one method of PRO. As kinematics affect the polyethylene wear of prosthesis, postcam engagement and paradoxical anterior motion may affect the longevity and PRO.[30] Thus, this study indicates the necessity of a future study, which would include long-term evaluations and several methods of PROs.

In conclusion, in vivo kinematics with the same anatomical articular surfaces after BCS and CR TKAs demonstrated different kinematics during deep knee bending motions. BCS TKA revealed more posterior femoral bicondylar roll-back and greater maximum flexion angle than CR TKA. There were no significant differences in the postoperative 2011 KSS between the two groups.

CONFLICT OF INTERESTS

The authors declare that there are no conflict of interests.

AUTHOR CONTRIBUTIONS

Tetsuya Tomita: Substantial contribution to research design; Teruya Ishibashi, Tetsuya Tomita, Takaharu Yamazaki, Shoji Konda, Masashi Tamaki: the acquisition, analysis and interpretation of data; Teruya

Ishibashi, Tetsuya Tomita: Drafting the paper and revising it critically; Kazuomi Sugamoto: revising the paper; Tetsuya Tomita: Approval of the submitted and final versions.

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