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Original Article

Anatomical bi-cruciate retaining TKA improves gait ability earlier than bi-cruciate stabilized TKA based on triaxial accelerometery data: A prospective cohort study

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ABSTRACT

Background: Total knee arthroplasty (TKA) is a common and cost-effective surgical treatment for osteoarthritis of the knee. However, only 82-89% of patients who performed TKA are satisfied with the postoperative outcomes. Therefore, bi-cruciate retaining (BCR) TKA is re-attracting attention. By retaining the anterior cruciate ligament (ACL), the knee may obtain the kinematic pathway that are closer to the native knee. The aim of the present study is to compare the ability to walk before and after surgery in patients who underwent bi-cruciate retaining total knee arthroplasty (BCR TKA) versus bi-cruciate stabilized (BCS) TKA during the early postoperative period.
Methods: Subjects included patients who underwent BCR TKA (10 knees) and BCS TKA (15 knees). We administered 10-meter gait tests before surgery and at 6 weeks and 3 months after surgery. We collected the following triaxial accelerometery data with a portable gait analyzer: walking time, number of steps, velocity, stride length, and coefficient of variability (CV) of double-leg support time while walking.
Results: Patients who underwent BCR TKA improved their gait ability [walking time ($p < 0.01$), number of steps ($p < 0.05$), velocity ($p < 0.01$), and stride length ($p < 0.01$) more than those who received BCS TKA at 6 weeks after surgery. BCR TKA improved gait ability (walking time, number of steps, velocity, and stride length) more than BCS TKA at 6 weeks after surgery. At 6 weeks after surgery, CV of double-leg support time while walking improved more in the BCR TKA group than in the BCS TKA group ($p < 0.05$).
Conclusions: BCR TKA is associated with improved gait ability in the early postoperative period.

Introduction

Total knee arthroplasty (TKA) is a common and cost-effective surgical treatment for osteoarthritis of the knee that has been shown to reduce pain and improve quality of life.[1–3] However, according to patient-reported outcome measures (PROMs), up to 19% of patients are not satisfied with the results of primary TKA.[4] Dissatisfaction following TKA is a well-documented phenomenon.[5] Pritchett revealed that patients who underwent bilateral staged TKA are more likely to prefer retention of their ACL and PCL or substituting with a medial pivot prosthesis.[6] Bi-cruciate retaining (BCR) TKA is regaining attention because ACL preservation results in kinematics that are more similar to those of native knees and potentially improves knee function and patient satisfaction after TKA more than posterior stabilized (PS) TKA BCS.[7,8] On the other hand, since there was proprioception at the tibial attachment of the ACL, there was concern that replacement of the cartilage surface with a prosthesis would interfere with the ability to walk.

Recently, an anatomical BCR TKA (Journey II XR; Smith&Nephew, Inc., Memphis, TN, USA) became available. It has new, unique anatomical design features, including an oblique 3° angle femorotibial joint line and an asymmetrical joint surface (Fig. 1). An oblique 3° angle femorotibial joint line resembles the joint line in a healthy knee. Thus, this feature may potentially

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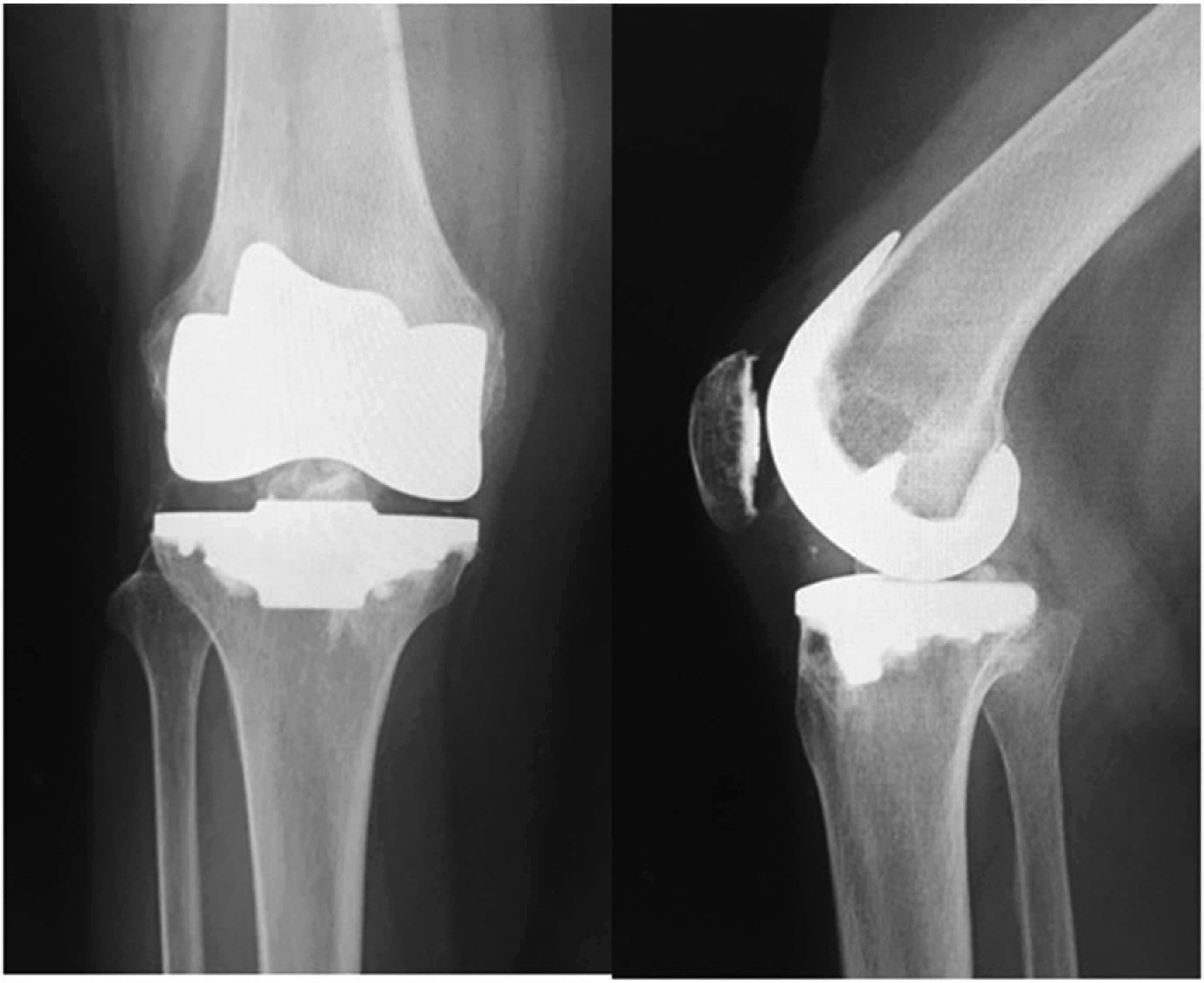

Fig. 1. Anatomical bi-Cruciate retaining TKA (Journey II XR; Smith + Nephew Inc., Memphis, TN, USA). The femoral condyle has an asymmetrical joint surface. The femorotibial joint line has an oblique 3° angle. The medial polyethylene insert has a concave design, while the lateral polyethylene insert has a convex design. Journey II XR reproduces anatomical geometry with osteotomy perpendicular to the mechanical axis.

improve postoperative clinical outcomes.[9] To the best of our knowledge, there have been no reports of gait analysis in patients who underwent BCR TKA using Journey II XR.

The hypothesis of the present study is that BCR TKA will improve gait ability in the early postoperative period. The aim of the present study is to compare the ability to walk before and after surgery in patients who underwent BCR TKA versus bi-cruciate stabilized (BCS) TKA (Journey II BCS; Smith&Nephew, Inc.), which is a compensatory design for bi-cruciate ligaments.

Material and methods

Participants and study subjects

Between 2019 and 2020, a prospective cohort study included consecutive patients who underwent TKA performed by a single surgeon (T.K.). The study included 10 patients (4 males and 6 females) with intact ACL and PCL who underwent BCR TKA. The control group consisted of 15 patients (3 males and 12 females) with a certain shape of ACL (frayed, partial, rupture and absent group)[10] who underwent BCS. Valgus deformity of the knee, rheumatoid arthritis, secondary osteoarthritis of the knee, severe extra-articular deformities, history of high tibial osteotomy, and knee joint infection and diseases that may affect postoperative recovery or gait due to the healthy knee, spine, hip, or ankle were excluded. Inclusion criteria of the present study were similar for both groups: 1) ability to walk independently for more than 30 m continuously without a cane before and after surgery and 2) varus osteoarthritis of the knee (Kellgren-Lawrence classification grade 4 or Ahlbäck classification grade 3 or 4).

Surgical procedure and rehabilitation

BCR and BCS TKA were performed using the measured resection technique. After inflating the tourniquet to 300 mmHg at the beginning of the procedure, subvastus arthrotomy was performed. Distal femoral osteotomy was performed at a valgus angle obtained during preoperative 3DCT planning using an intramedullary resection guide. Rotational alignment was adjusted to the surgical epicondylar axis of the femur. The anterior referencing technique was used for the posterior femoral cut. The size of the femoral component was determined based on the anteroposterior length of the femur, which was independent of the flexion gap. The smaller femoral component was chosen when the anteroposterior measurement fell in between sizes. An extramedullary resection guide was used for proximal tibial osteotomy. The angle of osteotomy was aimed perpendicular to the mechanical axis to recreate preoperative posterior inclination of the tibia based on preoperative 3DCT planning measurements in the coronal and sagittal planes. Rotational alignment of the tibia was defined as the anterior-posterior axis between the medial intercondylar tubercle and the medial border of the patellar tendon.[11] Between the two groups, the patella was resurfaced. For medial ligament balancing in extension, the deep layer of the medial collateral ligament (MCL) was released within 1 cm from the joint line for bone resection and surrounding osteophytes were removed. The superficial layer of the MCL, semimembranosus ligament, and posterior oblique ligament were not released. In both groups, weight bearing was not restricted and patients were allowed to walk with or without assistive devices on the first day after BCR and BCS TKA.

Gait analysis

The 10-m walk test was performed before surgery and at 6 weeks and 3 months after surgery. The measurement environment consisted of a 3-m runway, 10-m walkway, and 3-m deceleration path, with a total length of 16 m. Subjects waited in a static standing position at the start of the runway. They received a verbal instruction to walk as fast as they normally walk and a signal to start walking. Gait analysis was performed using the MG-M1100-HW gait analyzer (Mitsubishi Chemical Medience Corporation; Tokyo, Japan) to collect triaxial accelerometery data (Fig. 2). The measurement device was wrapped around the patient's third lumbar vertebra with a fixation band to position it in the third lumbar process. We investigated walking time (seconds), number of steps, walking rate (steps/minute), walking cycle time (seconds), coefficients of variation (CV) of double-leg support time, gait velocity (m/minute), and stride length (cm). CV is reported to be an indicator of gait stability, with higher values indicating greater variability in double-leg support time while walking [12.13.14]. To account for differences in preoperative gait ability between the two groups, percent improvement was calculated and compared from each gait parameter from before surgery to 6 weeks and 3 months after surgery, respectively.

The study design was approved by the institutional ethics review boards of the Ichinomiya Onsen Hospital Adult Reconstruction Center. All procedure performed were in accordance with the ethical standards of the institutional research committee.

Statistical analysis

Means and standard deviations are presented to describe the data. All *p*-values were two sided, and *p*-values of 0.05 or less were considered statistically significant. All statistical analyses were performed with EZR (Saitama Medical Center, Jichi Medical University; http://www.jichi.ac.jp.saitama-sct/Saitama HP. Files/statmedEN. Html, Kanda, 2012), which is a graphical user interface for R (The R Foundation for Statistical Computing; Vienna, Austria, version 2.13.0). More precisely, it is a modified version of R commander (version 1.6–3) that was designed to add statistical functions frequently used in biostatistics. Test reliability was calculated using SPSS version 24.0 (SPSS Inc., Chicago, Illinois, USA). Sample size was calculated using G* Power 3.1.9.4 software (Heinrich-Heine Universität Düsseldorf; Düsseldorf, Germany), which suggested that 25 knees are necessary for comparison of three groups with the following parameters: power = 0.85, alpha = 0.05, and effect size = 0.50.

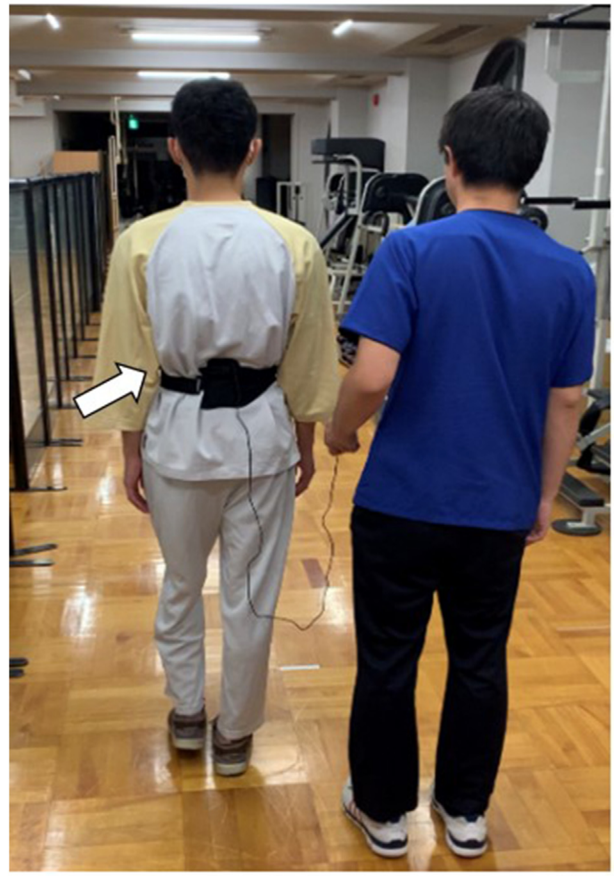

Fig. 2. Photograph showing gait measurements. The white arrow indicates the MG-M1100-HW gait analyzer (Mitsubishi Chemical Medience Corporation; Tokyo, Japan). The gait analyzer is wrapped around the patient's third lumbar vertebra with a fixation band to position it on the third lumbar process.

Results

Patient demographics including age, height, weight, and body mass index (BMI) are shown in Table 1. No significant differences were found between the two groups. The severity of deformity in the BCR group was Ahlbäck classification grade 3 in all 10 patients, and in the BCS group, 9 patients had Ahlbäck classification grade 3 and 6 patients had grade 4. The results of the 10-m gait analysis between the two groups before surgery, 6 weeks after surgery, and 3 months after surgery are shown in Tables 2–4. There were no

Table 1
Preoperative parameters between the two groups.

Parameters	BCR group (n = 10)			BCS group (n = 15)			*p* value
Age at surgery (years)	75	±	9.0	74.4	±	8.7	0.46
Height (cm)	154.9	±	9.7	158.5	±	7.4	0.29
Weight (kg)	59.3	±	15.0	63.3	±	5.0	0.31
BMI (kg / m^2)	24.3	±	3.7	25.3	±	2.1	0.33

Mean and standard deviation are presented.
Abbreviations: BMI, body mass index; BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized.

Table 2
Preoperative gait analysis.

Parameter	BCR group (n = 10)			BCS group (n = 15)			*p* value
Walking time (seconds)	9.5	±	2.7	12.5	±	4.1	0.13
Number of steps	18.2	±	3.5	20.78	±	2.93	0.14
Walking rate (steps/minute)	117.6	±	9.7	106.8	±	23.2	0.21
walking cycle time (seconds)	1.03	±	0.1	1.2	±	0.3	0.17
CV of double-leg support time (%)	6.5	±	3.5	5.5	±	3.4	0.35
Velocity (m / minute)	67.4	±	14.0	54.0	±	18.8	0.14
Stride length (cm)	56.6	±	9.1	49.0	±	7.5	0.12

Means ± standard deviations are presented.
Abbreviations: BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized; CV, coefficient of variation.

Table 3
Gait analysis at 6 weeks after surgery.

Parameter	BCR group (n = 10)			BCS group (n = 15)			*p* value	
Walking time (seconds)	9.20	±	1.2	13.7	±	2.9	0.01	**
Number of steps	18.1	±	2.1	23.6	±	3.8	0.02	*
Walking rate(steps/minutes)	118.4	±	6.7	105.6	±	13.9	0.07	
Walking cycle time (seconds)	1.0	±	0.1	1.16	±	0.2	0.09	
CV of double-leg support time (%)	4.5	±	3.3	7.1	±	1.8	0.11	
Velocity (m / minute)	66.2	±	9.2	45.8	±	9.1	0.01	**
Stride length (cm)	56.2	±	7.0	43.2	±	6.1	0.01	**

Means ± standard deviations are presented.
Abbreviations: BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized; CV, coefficient of variation.
* : $p < 0.05$, ** : $p < 0.01$.

Table 4
Gait analysis at 3 months after surgery.

Parameter	BCR group (n = 10)			BCS group (n = 15)			*p* value
Walking time (seconds)	8.8	±	1.6	9.8	±	1.9	0.21
Number of steps	17.1	±	3.4	18.1	±	2.8	0.32
Walking rate(steps/minute)	116.4	±	5.3	112.2	±	9.9	0.24
Walking cycle time (seconds)	1.0	±	0.1	1.1	±	0.1	0.23
CV of double-leg support time (%)	4.1	±	1.0	4.1	±	1.6	0.49
Velocity (m / minute)	70.2	±	10.5	63.4	±	11.46	0.20
Stride length (cm)	60.6	±	9.9	56.4	±	7.5	0.26

Means ± standard deviations are presented.
Abbreviations: BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized; CV, coefficient of variation.

significant differences between the two groups in any of the preoperative and 3-month postoperative measurements (Tables 2–4). At 6 weeks after surgery, there were significant differences between the two groups in walking time ($p < 0.01$), number of steps ($p < 0.05$), velocity ($p < 0.01$), and stride length ($p < 0.01$) (Table 3). The rate of change before to after surgery showed a significant difference for CV of double-leg support time while walking between before surgery and 6 weeks after surgery ($p < 0.05$) (Table 5, Fig. 3). There were no significant differences in the rate of change from before surgery to 3 months surgery for all parameters (Table 6, Fig. 3). In the BCR TKA group, CV of double-leg support time while walking was lower at 6 weeks and 3 months after surgery compared to before surgery, while CV values were higher in the BCS TKA group.

Regarding test reliability, the interclass and intraclass correlation coefficients for walking time (seconds), number of steps, walking rate (steps/minute), walking cycle time (seconds), gait velocity (m/minute), and stride length (cm) were strong. Coefficients for CV of double-leg support time (%) were reasonable (Table 7).

Table 5
Gait improvement from before surgery to 6 weeks after surgery.

Parameter	BCR group (n = 10)			BCS group (n = 15)			*p* value	
Walking time (seconds)	1.3	±	18.1	17.5	±	30.2	0.20	
Number of steps	1.0	±	12.1	14.4	±	15.8	0.11	
Walking rate (step/minute)	1.2	±	8.0	2.7	±	23.8	0.45	
Walking cycle time (seconds)	−0.3	±	7.2	1.7	±	17.6	0.42	
CV of double-leg support time (%)	−27.2	±	37.2	85.8	±	99.7	0.04	*
Velocity (m/minute)	2.0	±	22.1	−7.65	±	29.2	0.31	
Stride length (cm)	0.8	±	13.1	−10.9	±	13.3	0.12	

Values indicate percent improvement. Means ± standard deviations are presented.
Abbreviations: BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized; CV, coefficient of variation.
*$p < 0.05$.

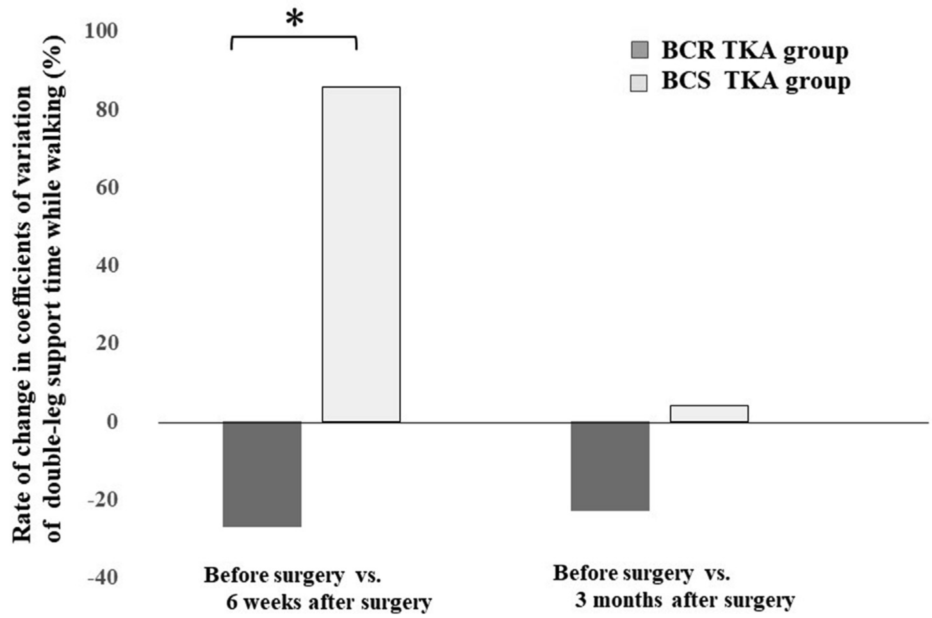

Fig. 3. Comparison of percent improvement in coefficients of variation of double-leg support time while walking before and after surgery, BCR; bicruciate retaining, BCS; bicruciate stabilized * <0.05.

Table 6
Gait improvement from before surgery to 3 months after surgery.

Parameter	BCR group (n = 10)			BCS group (n = 15)			*p* value
Walking time (seconds)	−5.3	±	8.3	−11.9	±	40.0	0.37
Number of steps	−6.3	±	4.4	−10.3	±	23.2	0.38
Walking rate (steps/minute)	−0.3	±	10.0	9.3	±	21.9	0.23
Walking cycle time (seconds)	1.1	±	8.9	−5.1	±	16.5	0.27
CV of double-leg support time (%)	−22.9	±	31.1	3.9	±	76.9	0.27
Velocity (m/minute)	6.0	±	9.0	32.4	±	49.9	0.18
Stride length (cm)	7.1	±	5.1	18.4	±	25.2	0.21

Values indicate percent improvement. Means ± standard deviations are presented.
Abbreviations: BCR, bi-cruciate retaining; BCS, bi-cruciate stabilized; CV, coefficient of variation.

Table 7
Test–retest reliability for gait analysis.

Parameter	Interclass correlation coefficient	Intraclass correlation coefficient
Walking time (seconds)	0.945	0.968
Number of steps	0.971	0.987
Walking rate (steps/minute)	0.924	0.969
Walking cycle time (seconds)	0.924	0.968
CV of double-leg support time (%)	0.695	0.848
Velocity (m/minute)	0.948	0.974
Stride length (cm)	0.968	0.988

Abbreviation: CV coefficient of variation.

Discussion

The most important findings of the present study were that 1) patients who underwent BCR TKA improved their gait ability (walking time, number of steps, velocity, and stride length) more than those who received BCS TKA at 6 weeks after surgery and 2) the BCR TKA group had more improvement in CV of double-leg support time while walking from before surgery to 6 weeks surgery than the BCS TKA group.

CV of double-leg support time while walking is an indicator of gait stability. A low CV indicates high gait stability.[12,13,14] In the BCR TKA group, CV of double-leg support time while walking was lower at 6 weeks and 3 months after surgery.

Kalaai et al.[15] reported that joint awareness (FJS-12) of the BCR TKA was not significantly reduced compared to the CR TKA at 3-year-follow-up, and since a functional ACL increases rotational stability and proprioception, future research should focus on kinematics in BCR TKA measured with gait analysis**.** In this study, early postoperative ACL proprioception was increased, which may have improved walking ability.

Kono et al.[16] reported that BCR TKA induced medial pivot motion similar to that of a normal knee in the preoperative group as well as in the preoperative group due to the anterior and posterior cruciate ligaments. It is possible that the same kinematics were reproduced in the present study, which allowed the patients to walk 6 weeks after surgery. In the Journey prosthesis, the femoral implant is positioned relatively anterior to the tibial implant and does not produce paradoxical motion. Therefore, unlike other implants, it is easier for the quadriceps muscle strength to function. In addition, there was no decrease in walking ability at 6 weeks postoperatively compared to preoperatively. In other words, BCR TKA group did not persist after 3 months, but the BCS TKA group improved.

Fujimoto et al.[17] reported that this phenomenon could be related to joint laxity. However, we previously reported that BCS TKA provides better mid-flexion stability than CR TKA.[18]

The BCS TKA design involves a bi-cruciate substitution system, namely a post-cam mechanism and a concave-convex orientation of the articular surface, like the normal knee. These features provide sufficient restraint against anterior translation of the femorotibial contact points in the mid-range of knee flexion. This finding suggests that BCS TKA provides greater restraint against anterior translation than cruciate retaining TKA. Tomite et al.[19] reported less anterior-posterior acceleration of the femoral component in the early stages of walking stance with BCS TKA versus CR TKA using triaxial accelerometer data. They demonstrated that BCS TKA is a design that does not give rise to paradoxical motion. Catani et al.[20] reported that during the stance phase to swing phase transition, BCS TKA was associated with an extension and flexion moment pattern consistent with biphasic quadriceps-hamstrings muscle activity as well as normal knees. Kono et al.[21] revealed that BCS TKA provides good functional stability during high-flexion weight-bearing activities. However, the BCS TKA group had higher CV of biped support time while walking at 6 weeks after surgery. In other words, the BCS TKA group had decreased gait stability at 6 weeks after surgery. BCS TKA is a functional approach that relies on the prosthesis for kinematics, whereas BCR TKA is an anatomical approach that relies on both cruciate ligaments for kinematics. In the BCS TKA group, a temporary decrease in walking ability was observed at 6 weeks postoperatively, suggesting that it took a certain period of time for the periarticular knee muscles, including the quadriceps, to function to compensate for the ACL and PCL kinematics. We have wondered if the BCS TKA group requires a longer learning curve because of the need to use the knee joint in a different way after surgery. In the BCR TKA group, the anterior and posterior cruciate ligaments guided the implants after surgery, which may have reproduced kinematics similar to that of normal knees starting in the early postoperative period. At 6 weeks and 3 months after surgery, CV of double-leg support time while walking was better than before surgery.

In the BCR TKA group, the anterior and posterior cruciate ligaments may induce a medial pivot movement in the same way as before surgery, which may have reproduced kinematics similar to that of normal knees early after surgery. At 6 weeks and 3 months after surgery, CV values for bipedal support time were better than before surgery. There are few reports of BCR TKA using Journey II XR. We have reported that BCR TKA improves mid-flexion stability to the same extent as BCS TKA, and postoperative lateral stability and medial laxity at 90° of flexion improves PROMs with BCR TKA.[9] BCR TKA can restore normal laxity and thus has the potential to offer more normal knee function with cadaveric specimens.[22] Kono et al.[16] reported that from 30° to 120° of flexion, the lateral side of BCR TKA knees is located significantly more anteriorly than that of normal and unicompartmental arthroplasty knees. The significance of retaining both cruciate ligaments might be seen in analysis of early postoperative gait function. It is necessary to evaluate muscle activity and kinematics during walking as well as gait analysis, because it is not possible to clarify the factors affecting gait ability without these additional evaluations.

This study contains some limitations. First, the number of study participants was small and the design of this study is a consecutive cofort study, and we plan to conduct a paired matched study with a larger number of patients. In addition, the study participants included only patients who had primary osteoarthritis of the knee with varus deformity. Therefore, the results of the present study are not necessarily applicable to other diseases and deformities. Second, the postoperative observation period was very short. Larger prospective studies with mid-term and long-term outcomes are required to further substantiate our findings. Third, we did not investigate postoperative clinical outcomes such as patient subjective questionnaires. Fourth, we have not been able to identify factors that affect gait ability. Future research should focus on knee kinematics in BCR and BCS TKA investigated with gait studies using 2D and 3D registration under fluoroscopy and 3-dimensional action analysis.

Conclusion

Based on triaxial accelerometery data, BCR TKA improved gait ability (walking time, number of steps, velocity, and stride length) more than BCS TKA at 6 weeks after surgery. At 6 weeks after surgery, CV of double-leg support time while walking improved more in the BCR TKA group than in the BCS TKA group.

Funding

No external sources of funding were used.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committees and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Institutional review board approval for the study was provided by the Ichinomiya Onsen Hospital Adult Reconstruction Center (H19003).

Informed consent

Informed consent was obtained from all individual participants included in the present study.

Declaration of competing interest

All authors have no potential conflicts of interest, including financial interests, activities, relationships, and affiliations, to disclose.

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