Knee kinematics in bi-cruciate stabilized total knee arthroplasty during squatting and stair-climbing activities

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ABSTRACT

This study aimed to evaluate clinical outcomes and in vivo kinematics of bi-cruciate stabilized (BCS) total knee arthroplasty (TKA), using image-matching techniques. We analyzed tibiofemoral anteroposterior translation, axial rotation, and anterior/posterior cam-post contact for 22 BCS TKAs during squatting and stair-climbing. The functional activities on the 2011 Knee Society Score were significantly improved from 36 to 71. The tibiofemoral translation and axial rotation during squatting/stair-climbing were 16.1 mm/7.1 mm and 2.5° external/1.1° internal, respectively. Anterior/posterior cam-post contacts were observed during squatting (14%/96%) and stair-climbing (27%/96%). In conclusion, BCS TKA produced physiological sagittal plane kinematics during activities with favorable clinical outcomes.

1. Introduction

The most important aims of total knee arthroplasty (TKA) are to achieve pain relief with improved function in patients with late-stage knee osteoarthritis. Over the last two decades, the proportion of younger and more physically active patients undergoing TKA has increased. Despite innovations in prosthesis design and surgical techniques, TKA has not completely restored normal knee kinematics and some daily activities could be limited compared to healthy knees; 52% of patients after TKA reported some degree of limitation in performing functional activities.¹ A report showed that only 72% of patients were satisfied with the pain relief and the ability to climb and descend stairs.² Moreover, patients after TKA are reported as feeling “artificial” when loaded in flexion during activities.³

There have been several reports on unphysiological kinematics after TKA, including decreased/paradoxical anteroposterior (AP) translation, and limited/reverse axial rotation of the femur with respect to the tibia with flexion.^{4,5} The reasons for abnormal kinematics were thought to be related to a symmetric articular configuration and deficiency of the anterior cruciate ligament (ACL), regardless of cruciate-retaining and posterior-stabilized (PS) prostheses.⁶ In addition, other cited causes of

abnormal kinetics included the impingement of the anterior post, inappropriate tension of the posterior cruciate ligament (PCL), and dysfunction of the cam-post mechanism.⁴ Native knee motion is guided by the collateral and cruciate ligaments and the surface geometry of the concave medial and convex lateral tibial plateau, the asymmetric femoral condyles,⁷ as well as external forces. Meanwhile, knee motion after TKA is guided by the collateral ligaments, the surface geometry and, occasionally, by retained PCL or cam-post mechanisms,^{7,8} depending on the posture.⁷

Kinematic analysis is important for understanding normal and pathologic joint function and could have a direct effect on patients' functional outcome and satisfaction. This study aimed to analyze the dynamic kinematics of the knee joint and the anterior/posterior cam-post mechanism during squatting and stair-climbing in bi-cruciate stabilized (BCS) TKA, measured using radiographic-based image-matching techniques.

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2. Methods

2.1. Patients

The study protocol was approved by our Institutional Review Board (IRB number 24–166). This prospective cohort study involved 20 patients with 22 varus knees. The patients had undergone BCS fixed-bearing TKA (JOURNEY II, Smith & Nephew, Memphis, TN, USA), with more than 12-months of follow-up, were prospectively recruited for the study, and provided their consent to participate. Patients with a history of neuromuscular disease, fractures around the knee joint, previous arthroplasty and osteotomy, and severe extra-articular deformity were excluded.

BCS TKA has asymmetrical anatomical femoral condyles, a tibial baseplate with concave medial and convex lateral polyethylene articular surfaces, and anterior and posterior cam-post mechanisms.⁹ A 3° medial inclination of the articular surfaces, relative to the tibial baseplate, was implemented by including a 2.5-mm difference in the thickness of the medial and lateral compartments.⁹ This knee system is designed to function with an anterior cam-post mechanism below 20° of knee flexion to limit anterior tibial translation and, therefore, partially replicate the function of the ACL. The posterior cam-post mechanism engages from 60° to 70° knee flexion and promotes physiological femoral rollback.

2.2. Surgical technique

Between November 2013 and June 2015, all TKAs were performed by a single experienced surgeon (KO), using a similar standardized technique based on the mechanical alignment and medial parapatellar approach. Using a measured resection technique, the femoral and tibial components were aligned perpendicular to the mechanical axes in the coronal plane by cutting the distal femoral and proximal tibial bone at 90° to their respective mechanical axes with intramedullary and extramedullary instruments, respectively. In the sagittal plane, the femoral component was aligned perpendicular to the distal anatomical axis of the knee and resection of the proximal tibia was planned to obtain a 3° posterior tilting using extramedullary guides according to the manufacturer's recommendation. In the axial plane, the femoral component was aligned along the surgical epicondylar axis, with the rotational alignment of the tibial component adjusted to the AP axis of the tibia. Additionally, the rotational alignment of the tibial component was also confirmed using the range of motion (ROM) technique as a reference. Soft tissue balancing was performed to achieve near-normal medial stability in knee extension and flexion and lateral extension laxity was acceptable.^{10,11}

2.3. Patient-reported outcomes

Pre- and postoperative patient-reported outcomes were assessed using the 2011 Knee Society Score (KSS 2011). The subjective component of KSS 2011 evaluates the following: symptoms, satisfaction, and functional activities (walking and standing, standard activities, advanced activities, and discretionary activities). The maximum possible score for each component of the KSS 2011 is as follows: 25 for 'symptoms'; 40 for 'patient satisfaction'; 100 for 'functional activities'; 5 for 'squatting'; and 5 for 'climbing up or down a flight of stairs'.

2.4. Berg balance scale (BBS)

BBS was developed as a performance-oriented measure of balance in elderly individuals. BBS is a common tool for balance assessment and can be considered a reference standard for clinically assessing balance in patients with TKA, with good reliability and validity.¹² The utility includes grading different patients' balance abilities, monitoring functional balance over time, and evaluating patients' responses to

treatment. BBS is a test of 14 items; it is performance based and has a scale of 0–4 for each item (higher score for independent performance), with a maximum score of 56.

2.5. Radiographic measurements

Pre- and postoperative whole-leg radiographs were taken with the patella facing a forward position, with the feet straight and at shoulder width. The hip-knee-ankle (HKA) angle was defined as the coronal angle between the mechanical axes of the femur and the tibia. Positive and negative values were expressed as varus and valgus, respectively. The coronal femoral component angle was defined as the medial angle formed by the mechanical axis of the femur and the horizontal axis of the medial and lateral femoral condyles calibrated by subtracting the 3° lateral incline of the articular surfaces of the femoral condyles. The coronal tibial angle was defined as the medial angle between the mechanical axis of the tibia and the horizontal axis of the tibial component. The sagittal femoral angle was defined as the angle between the anatomical axis of the distal femur and a line that was drawn perpendicular to the distal point of the femoral component. The tibial posterior slope was defined as the angle between a line that was perpendicular to the anatomical axis of the proximal tibia and a line that was drawn across the tibial tray.

2.6. Kinematic analyses

Periodic sagittal radiographs were obtained during two dynamic movements under radiographic surveillance, using a flat-panel detector (FPD: Ultimix-I, Toshiba, Tochigi, Japan) operating at 10 frames per second, with an image area size 420 (horizontal) × 420 (vertical) mm, and 0.274 × 0.274 mm/pixel resolution.^{13,14} For squatting, subjects crouched downward from a standing position to where the knees were maximally flexed. For stair-climbing, subjects were assessed using a reciprocal stepping pattern, for a step height of 20 cm. The manufacture provided three-dimensional (3D) computer-aided design (CAD) models of the femoral and tibial components that were projected and superimposed onto the serial two-dimensional radiographic images acquired using the FPD.¹¹ Using image-matching techniques with a 3D CAD model to analyze the surfaces of the femoral and tibial components, we evaluated the dynamic in vivo kinematic parameters: tibiofemoral implant flexion angle, AP translation, and axial rotation. The positive or negative value of tibiofemoral flexion was defined as flexion or extension of the femoral component relative to the tibial component, respectively. The positive or negative value of AP tibiofemoral position was defined as anterior or posterior to the midline of the tibial tray, respectively. The positive or negative value of axial rotation was defined as the internal or external rotation of the femoral component relative to the tibial component, respectively. Simultaneously, the occurrences of contact between the anterior/posterior cam and the post were determined by the intersection of the femoral component and the tibial post, while assessing the configuration of the articular surfaces of the polyethylene insert.^{4,13} A previous study estimated the root mean square errors for the femoral component relative to the tibial component to be 0.25 mm for in-plane translation, 0.28 mm for out-of-plane translation, and 0.27° for rotation.¹⁴

2.7. Statistical analyses

Statistical analysis was performed using JMP Software (Version 11.0; SAS Institute Inc., Cary, NC, USA). All values are expressed as the mean ± standard deviation. Welch's *t*-test and chi-squared tests were used to evaluate differences in demographic and radiographic data between pre- and postoperative TKAs. A repeated-measures analysis of variance and post hoc tests (Student's *t*-test) were used to analyze the kinematics, including the total amount of AP translation and axial rotation, and the flexion angle and AP position for the contact between

Table 1
Demographic and radiographic data.

	Total knees (n = 22)
Age (years)	73.5 ± 6.6
Sex (female/male)	20/2
Diagnosis (OA/RA)	21/1
BMI (kg/m ²)	27.7 ± 4.2
Duration of postoperative follow-up (years)	1.1 ± 0.2
Coronal femoral component angle (°)	89.2 ± 1.7
Coronal tibial component angle (°)	90.8 ± 1.4
Femoral flexion angle (°)	86.9 ± 2.6
Tibial posterior slope (°)	2.2 ± 2.4

Notes: OA, osteoarthritis; RA, rheumatoid arthritis; BMI, body mass index; BCS, bi-cruciate stabilized; values are expressed as the mean (standard deviation).

the anterior/posterior cam and post between the two activities. Pearson's chi-squared test was used to analyze the difference between the two activities for the proportion of contact between the anterior/posterior cam and post. Probability values (P-values) less than 0.05 were considered statistically significant. Power analyses indicated that a sample size of about 22 knees per activity would provide a statistical power of 80% for detecting between-activity differences of 5.0 mm in AP translation of the femoral component relative to the tibial component, assuming a p-value < 0.05 and standard deviation of 4.0 mm.

3. Results

Relevant pre- and postoperative patient information are presented in **Tables 1 and 2**. Compared to preoperatively, the functional activities on the 2011 KSS and BBS were significantly ($p < 0.05$) improved postoperatively from 35.7 ± 15.1 to 70.9 ± 17.7 and from 52.1 ± 4.4 to 54.5 ± 1.2 , respectively.

The knee kinematics during squatting and stair-climbing are presented in **Table 3** and **Figs. 1 and 2**. The BCS TKAs produced physiological anterior/posterior translation of the femoral component on the tibial component with increasing knee extension/flexion. The associated amounts of AP tibiofemoral translation during squatting and stair-climbing were 16.1 ± 4.2 mm and 7.1 ± 2.6 mm, respectively, with a significant difference ($p < 0.05$) (**Fig. 1A**). AP translation during squatting was larger than for stair-climbing ($p < 0.001$). The total amounts of femoral rotation relative to the tibial baseplate during squatting and stair-climbing were $2.5 \pm 4.0^\circ$ external and $1.1 \pm 5.3^\circ$ internal, respectively, with a significant difference ($p < 0.05$) (**Fig. 1B**).

Anterior cam-post contacts after BCS TKA were observed during squatting (13.6%) and stair-climbing (27.3%). Anterior contact during squatting and stair-climbing started at less than $-4.3 \pm 3.7^\circ$ and $-2.0 \pm 5.4^\circ$ of flexion, respectively (**Fig. 2**). There were high rates of posterior cam-post contact during both squatting (95.5%) and stair-climbing (95.5%). Posterior contact during squatting and stair-climbing started at more than $75.8 \pm 13.3^\circ$ and $63.9 \pm 10.3^\circ$ of flexion,

Table 2
Comparison of pre- and postoperative clinical data.

	Preoperative (n = 22)	Postoperative (n = 22)	P-value
HKA angle (°)	11.3 ± 4.1	-0.1 ± 2.6	< 0.001 [*]
ROM (Extension/Flexion, °)	-9.1 ± 5.0/119.4 ± 14.6	-0.2 ± 1.1/127.5 ± 8.3	< 0.001 [*] /0.047 [*]
KSS 2011: Symptoms (25)	5.5 ± 3.7	21.1 ± 3.8	< 0.001 [*]
Satisfaction (40)	12.2 ± 4.5	27.5 ± 9.1	< 0.001 [*]
Functional activities (100)	35.7 ± 15.1	70.9 ± 17.7	< 0.001 [*]
Squatting (5)	1.4 ± 1.5	3.6 ± 1.5	< 0.001 [*]
Climbing up or down a flight of stairs (5)	1.3 ± 0.6	3.7 ± 1.1	< 0.001 [*]
BBS (56)	52.1 ± 4.4	54.5 ± 1.2	0.033 [*]

Notes: TKA, total knee arthroplasty; BCS, bi-cruciate stabilized TKA; HKA, hip-knee-ankle; ROM, range of motion; KSS, Knee Society Score; BBS, Berg Balance Scale; values are expressed as the mean (standard deviation).

* $P < 0.05$.

Table 3
Kinematic data during squatting and stair-climbing.

	Squatting	Stair-climbing	P-value
AP translation during activity (mm)	16.1 ± 4.2	7.1 ± 2.6	< 0.001 [*]
Axial rotation during activity (°)	-2.5 ± 4.0	1.1 ± 5.3	0.025 [*]
Anterior cam-post contact (%)	13.6	27.3	0.262
Posterior post-cam contact (%)	95.5	95.5	1.000
Flexion angle at anterior cam-post contact (°)	-4.3 ± 3.7	-2.0 ± 5.4	0.869
Flexion angle at posterior cam-post contact (°)	75.8 ± 13.3	63.9 ± 10.3	0.004 [*]
AP position at anterior cam-post contact (°)	1.3 ± 0.8	0.9 ± 1.2	0.944
AP position at posterior cam-post contact (°)	-6.7 ± 4.1	-3.3 ± 2.8	0.004 [*]

Notes: BCS, bi-cruciate stabilized TKA; TKA, total knee arthroplasty; AP, anteroposterior (+, anterior; -, posterior); axial rotation (+, internal; -, external). Values are expressed as the mean (standard deviation).

* $P < 0.05$.

respectively (**Fig. 2**).

4. Discussion

To our knowledge, this is the first in vivo study describing the 3D dynamic kinematics during two weight-bearing activities after BCS TKAs (JOURNEY II). The femoral component exhibited physiological sagittal kinematics relative to the tibial component with a small amount of axial rotation during squatting and stair-climbing. The cam-post mechanism at the anterior/posterior aspect of the post functioned during knee extension, particularly towards hyperextension, and from 60° of flexion onward. The BCS TKA designs produced reproducible kinematics due to a compensatory mechanism for the cruciate ligaments and an asymmetrical tibial articular geometry, which also provided intrinsic joint stability and contributed to favorable clinical outcomes.

In this study, the BCS TKAs produced approximately 16 mm of posterior translation of the femoral component on the tibial baseplate during squatting. Healthy knees have been reported to generate approximately 20 mm of posterior femoral rollback during squatting from 0° to 120° of knee flexion.¹⁵ The posterior femoral translation with the BCS TKAs relatively approached normal knee values and was larger compared to those of other TKA designs, of approximately 6–12 mm, as determined in previous studies.^{6,16} Physiological femoral rollback with appropriate rotational alignment is acceptable to prevent the incidence of ITB friction syndrome in the guided motion implant. Additionally, contrary to a previous TKA study,⁵ paradoxical femoral translation was rarely observed in the present study. Certainly, our squatting and stair-climbing-related results demonstrated constant AP translation throughout the entire range of knee flexion/extension. Restoration of physiological sagittal kinematics might result in subsequent

Fig. 1. The average anteroposterior (AP) translation (+, anterior; −, posterior: A) and axial rotation angle (+, internal; −, external: B) of the femoral component, relative to the tibial component for the bi-cruciate stabilized total knee arthroplasties (TKA) and healthy knees. The blue, red, and black lines represent squatting (TKA), stair-climbing (TKA), and squatting (Healthy), respectively. The error bars represent one standard deviation. The kinematics data for healthy subjects were derived from the previous study.¹³

Fig. 2. Percentage of the bi-cruciate stabilized total knee arthroplasties where the cam-post contact occurred at a certain tibiofemoral flexion angle reported for the two activities. Anterior and posterior parts of the cam-post are shown. The blue and red lines represent squatting and stair-climbing, respectively.

improvement in patient-reported clinical outcomes and balance function in terms of the progress measured by KSS and BBS.¹²

The BCS femoral component rotations relative to the tibial baseplate were different between squatting and stair-climbing in this study and smaller than in healthy knees.¹⁷ Dennis et al reported that a medial pivot pattern in flexion was present in only 55% of patients in the analysis of 811 TKAs with several designs, suggesting that surgeons have little ability to reliably induce a particular kinematic pivot pattern in TKA.¹⁸ The femoral external rotation of the JOURNEY I has been reported to be an average of 10° during deep knee flexion.^{3,8} A small axial rotation without apparent medial pivot pattern or screw home movement was demonstrated in this study due to preoperative residual decreased rotation and improved allowance of implant rotation, preventing the ITB syndrome noted in JOURNEY I. Following JOURNEY II BCS TKA, axial rotational kinematics were not fully restored and were significantly lower compared to those of normal knees.^{8,17}

In this study, we identified that the AP tibiofemoral position was actually anterior relative to the tibial component at knee extension during the two activities even when anterior cam-post engagement did not necessarily occur. Anterior cam-post contact during squatting and stair-climbing was reported to occur in 63% and 33% of TKAs, respectively, after NexGen LPS TKA.^{4,19} Belvedere et al recently reported that anterior contact occurred in 40–60% of patients after JOURNEY I at knee extension during chair-rising, stair-climbing, and step-up.²⁰ Anterior cam-post contact after JOURNEY II BCS TKA was relatively

low in this study during squatting (14%) and stair-climbing (27%) near extension. This finding suggests that the cam-post design for the JOURNEY II BCS TKA could result in lower cam-post stresses, thus reducing the risk for failure of the tibial post. The engagement of the posterior cam-post experienced in almost all cases might increase AP stability during squatting and stair-climbing. Catani et al reported that for JOURNEY I, posterior contact occurred at approximately 50–60° during chair-rising, step-up, and step-down activities.¹⁹ For the cam-post contacts, the variability observed among patients and activities may be due to the subject-specific action of active muscle contraction, which are necessary for knee balancing during highly demanding weight-bearing activities.²⁰

The limitations of our study should be considered during the interpretation of our results. First, the present study was limited by the small number of patients. However, this was a prospective study and selection bias was absent in the surgical allocation of patients. Second, this study focused on the evaluation of patients with end-stage varus osteoarthritic knees. Other conditions, such as valgus osteoarthritis, would have potential effects on the kinematic results. Third, after TKA, patients might still retain preoperative activity patterns. Further investigation will be necessary to identify the relationship between pre- and postoperative knee kinematics and patient-derived functional outcomes. Additional studies are required to analyze the effect of kinematics based on various patient characteristics, implant alignment, ligament balance, and surgical technique.²¹

5. Conclusion

This study showed that patients exhibited improved clinical outcomes and sagittal plane physiological kinematics during squatting and stair-climbing after BCS TKA. The reproducible stable tibiofemoral translation during dynamic motions was most likely caused by the morphological characteristics of the prosthesis, the high conformity between the medial tibiofemoral articulating surfaces, and the anterior/posterior cam-post mechanism.

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Conflict of interest

All authors declare that they have no conflicts of interest.

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