Published online: 2020-10-27

Gait and Knee Flexion In Vivo Kinematics of Asymmetric Tibial Polyethylene Geometry Cruciate Retaining Total Knee Arthroplasty

Christian Klemt, PhD[1] John Drago, SB[1] Ruben Oganesyan, MD[1] Evan J. Smith, MD[1] Ingwon Yeo, MD[1] Young-Min Kwon, MD, PhD[1]

[1] Bioengineering Laboratory, Department of Orthopaedic Surgery, Massachusetts General Hospital, Harvard Medical School, Boston, Massachusetts

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Address for correspondence Young-Min Kwon, MD, PhD, Department of Orthopaedic Surgery, Massachusetts General Hospital, Harvard Medical School, 55 Fruit Street, Boston, MA 02114 (e-mail: ymkwon@mgh.harvard.edu).

Abstract

The preservation of the posterior cruciate ligament in cruciate retaining (CR) total knee arthroplasty (TKA) designs has the potential to restore healthy knee biomechanics; however, concerns related to kinematic asymmetries during functional activities still exist in unilateral TKA patients. As there is a limited data available regarding the ability of the contemporary CR TKA design with concave medial and convex lateral tibial polyethylene bearing components to restore healthy knee biomechanics, this study aimed to investigate in vivo three-dimensional knee kinematics in CR TKA patients during strenuous knee flexion activities and gait. Using a combined computer tomography and dual fluoroscopic imaging system approach, in vivo kinematics of 15 unilateral CR TKA patients (comparison of replaced and contralateral nonreplaced knee) were evaluated during sit-to-stand, step-ups, single-leg deep lunge, and level walking. The patient cohort was followed-up at an average of 24.5 months (± 12.6, range 13–42) from surgical procedure. Significantly smaller internal knee rotation angles were observed for the contemporary CR TKA design during step-ups (2.6 ± 5.8 vs. 6.3 ± 6.6 degrees, $p < 0.05$) and gait (0.6 ± 4.6 vs. 6.3 ± 6.8 degrees, $p < 0.05$). Significantly larger proximal and anterior femoral translations were measured during sit-to-stand (34.7 ± 4.5 vs. 29.9 ± 3.1 mm, $p < 0.05$; -2.5 ± 2.9 vs. -8.1 ± 4.4 mm, $p < 0.05$) and step-ups (34.1 ± 4.5 vs. 30.8 ± 2.9 mm, $p < 0.05$; 2.2 ± 3.2 vs. -3.5 ± 4.5 mm, $p < 0.05$). Significantly smaller ranges of varus/valgus and internal/external rotation range of motion were observed for CR TKA, when compared with the nonoperated nee, during strenuous activities and gait. The preservation of the posterior cruciate ligament in the contemporary asymmetric bearing geometry CR TKA design with concave medial and convex lateral tibial polyethylene bearing components has the potential to restore healthy knee biomechanics; however, the study findings demonstrate that native knee kinematics were not fully restored in patients with unilateral asymmetric tibial polyethylene bearing geometry CR TKA during functional activities.

Keywords

- cruciate retaining total knee arthroplasty
- in vivo 6DOF kinematics
- sit-to-stand
- step-ups
- single-leg deep lunge
- gait

received
April 28, 2020
accepted
September 6, 2020

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DOI https://doi.org/10.1055/s-0040-1718681.
ISSN 1538-8506.

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Knee osteoarthritis (OA) is a leading cause of disability,[1] with patients suffering from joint pain, stiffness, and functional impairments that affect functional activities of daily living.[2] Over 1.5 million total knee arthroplasties (TKAs) are performed annually worldwide for the treatment of end-stage knee OA.[3] Although TKAs have effectively reduced pain and improved self-reported physical function in patients with end-stage knee OA,[4] movement asymmetries may persist several years after knee joint replacement surgery.[5–7] As patients are younger and more active,[8,9] the impact of movement asymmetries on functional daily activities may increase,[10] necessitating the design of TKAs that are able to better restore healthy in vivo knee kinematics.

Cruciate retaining (CR) TKAs were designed to improve proprioception, restore femoral rollback, and reproduce physiological knee biomechanics through the preservation of the posterior cruciate ligament (PCL).[11,12] Thus, it has been suggested that CR TKA has the potential to improve functional outcomes and patient satisfaction.[13] However, in vivo fluoroscopic analyses have demonstrated that CR TKA does not fully restore healthy knee kinematics.[14,15] These studies reported that patients implanted with CR TKA designs have exhibited less posterolateral femoral rollback as the knee moves from full extension to flexion, abnormal axial rotation between the femur and the tibia throughout the range of movement, as well as a different center of rotation of the knee in the horizontal plane. These significantly altered kinematic knee joint biomechanics have been suggested as one of the potential contributory factors resulting in up to 33% of patients remaining dissatisfied following TKA.[16]

A new CR TKA design (Journey II Total Knee System, Smith & Nephew, Memphis, TN) with asymmetric tibial polyethylene bearing geometry was recently introduced to optimize in vivo knee kinematics. The contemporary asymmetric bearing geometry CR TKA design exhibits concave medial and convex lateral tibial polyethylene bearing components to more physiologically mimic the native knee joint. Additionally, a high medial lip was introduced to provide anterior stability through replication of the anterior cruciate ligament function in full extension. Despite the potential of the newly designed asymmetric tibial polyethylene bearing geometry CR TKA to improve functional and clinical patient outcomes, there is a paucity of data available in the literature regarding the ability of the contemporary CR TKA design to restore healthy knee kinematics during functional daily activities. The precise knowledge of in vivo knee kinematics during functional tasks is essential as abnormal knee kinematics have implications on wear characteristics and implant longevity, in addition to patient satisfaction.[17,18] As knee flexion activities as well as gait are essential for everyday life, this study aimed to investigate in vivo three-dimensional (3D) kinematics of the contemporary CR TKA design with asymmetrical tibial polyethylene components during step-ups, sit-to-stand, single-leg deep lunge, and gait utilizing a validated dual fluoroscopic imaging system (DFIS).

Materials and Methods

Patients

This study evaluated 15 well-functioning patients (68.4 ± 5.86 years; 6 males, 9 females) without history of any surgical complications that were implanted unilaterally with an asymmetrical tibial polyethylene bearing geometry CR TKA (Journey II Total Knee System, Smith & Nephew). The in vivo knee kinematic performance between CR TKA and the contralateral nonoperated knee was compared. All patients in this study presented no radiographic signs of OA in the contralateral nonoperated knee. All patients also had no other symptomatic joints in either lower extremity as well as no back/radicular symptoms. The average body weight and height were 80.1 kg ($\pm$20.2, range 52–113) and 161.5 cm ($\pm$13.6, range 130–180), respectively (►**Table 1**). The sizes for femoral and tibial components were 4.9 ($\pm$1.5, range 3–8) and 4.1 ($\pm$1.5, range 2–7), respectively, with tibial polyethylene bearing component thicknesses of 9.9 ± 1.3 (9.0–13.0) and 9.9 ± 1.3 (9.0–13.0) for medial and lateral compartments (►**Table 1**). The patient cohort was followed-up at an average of 24.5 months ($\pm$12.6, range 13–42) from surgical procedure.

Three-Dimensional In Vivo Knee Kinematic Analysis

All 15 patients underwent a computed tomography scan (Sensation 64, Siemens, Germany, 140 kVp, image resolution 512×512 pixels, voxel size $0.97 \times 0.97 \times 0.60\ mm^3$) for the development of 3D models of both asymmetrical tibial polyethylene bearing geometry CR TKA as well as nonoperated knee. A previously published 3D mirroring technique was utilized to establish the coordinate frames of the operated knee,[19] with the mirroring technique allowing for the minimization of residual surface-to-surface registration errors between the remaining bone on the operated side and the mirrored nonoperated one (►**Fig. 1**). Anatomical bony landmarks were utilized to construct local coordinate frames for the femur and tibia of the nonoperated knee.[20] The knee rotation angles were

Table 1 Demographic data of cruciate retaining total knee arthroplasty (TKA) patients

$N = 15$	Average ± standard deviation (range)
Age (y)	68.4 ± 5.8 (60.5–80.6)
Gender	9 female, 6 male
Laterality	11 right, 4 left
BMI (kg/m^2)	31.2 ± 9.9 (19.6–60.9)
Follow-up (mo)	14.5 ± 12.6 (0.7–42.2)
Femoral component size	4.9 ± 1.5 (3.0–8.0)
Tibia component size	4.1 ± 1.5 (2.0–7.0)
Polythickness medial (mm)	9.9 ± 1.3 (9.0–13.0)
Polythickness lateral (mm)	9.9 ± 1.3 (9.0–13.0)

Abbreviation: BMI, body mass index.

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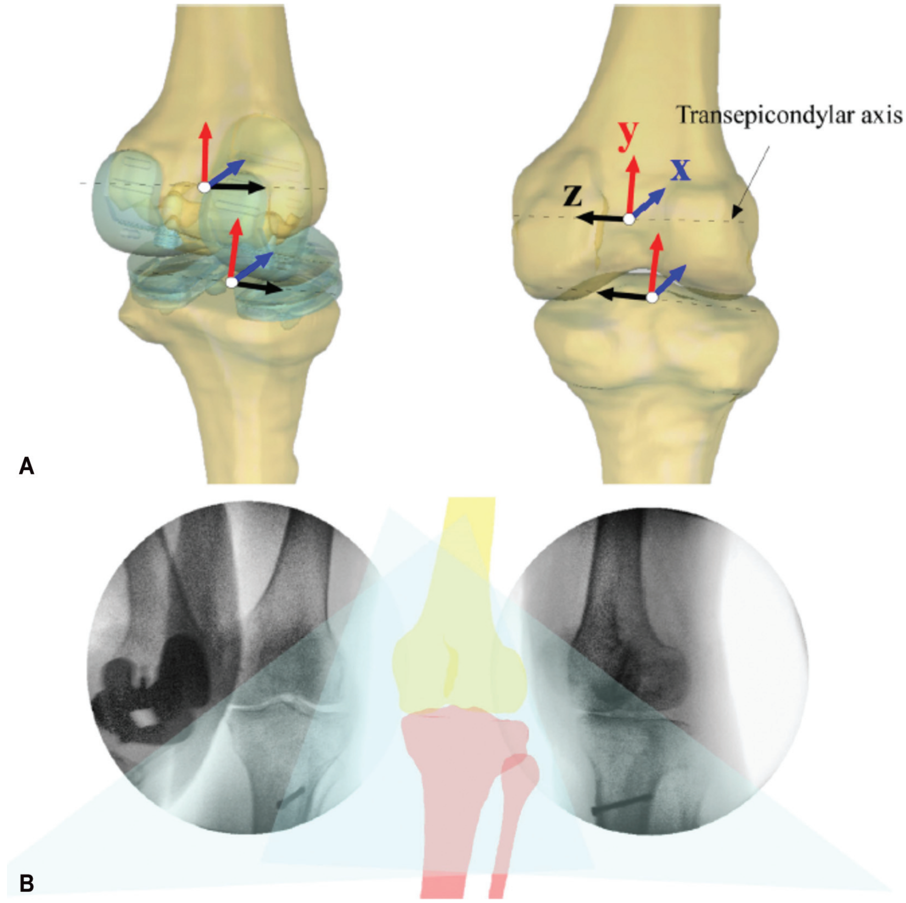

Fig. 1 (**A**) Three-dimensional (3D) knee model of unilateral cruciate retaining (CR) total knee arthroplasty (TKA) patient reconstructed from computed tomography (CT) images. The transepicondylar axis (TEA) was defined as the medial/lateral axis and the midpoint of this axis as the femoral center. The cross product of the TEA and the long axis was defined as the anterior/posterior axis. Two circles were created to fit the medial and lateral plateaus separately. The line connecting the centers of these two circles was defined as the medial/lateral axis and the midpoint as the tibial center. The cross product of the medial/lateral axis and the proximal tibial long axis was the anterior/posterior axis of the tibia. The anatomical coordinate systems of the operated knee were determined using a 3D mirroring technique. (**B**) The CT-based 3D knee bony models were matched to the silhouettes of the corresponding bones in the fluoroscopic images.

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calculated using a Cardan angle sequence (flexion/extension, adduction/abduction, internal/external rotation).[21] Translations of the knee were represented along the anterior/posterior, medial/lateral, and superior/inferior directions of the tibia. The six degrees of freedom (6DOF) range of motion (ROM) was calculated as the maximum value minus the minimum value during step-ups, sit-to-stand, and gait.

All unilateral CR TKA patients performed level walking on a treadmill at a self-selected speed, step-ups, sit-to-stand, and single-leg deep lunge under DFIS surveillance (BV Pulsera, Phillips Medical, USA) using snapshots (with an 8-ms pulse width, 60–80 kV, and 0.042–0.066 mAs). The two-dimensional fluoroscopic images and the 3D subject-specific knee models were imported into the virtual DFIS environment for determination of knee positions. The knee model was registered when its projection to the virtual image intensifiers best matches the fluoroscopic outlines of the actual knee[22] (►**Fig. 1B**). A cubic spline interpolation was performed to obtain continuous data during the functional activities.

Statistical Analysis

The Wilcoxon signed-rank test was performed to determine significant differences in in vivo knee kinematics during functional daily activities between asymmetrical tibial polyethylene bearing geometry CR TKA and the nonoperated knees ($\alpha = 0.05$).[23]

Results

In Vivo 6DOF Kinematics

There are no significant differences in knee flexion/extension between asymmetrical tibial polyethylene bearing geometry CR TKA and the native knee during sit-to-stand (44.1 ± 10.7 vs. 42.2 ± 12.9 degrees; ►**Fig. 2A**). Throughout the first 41% of the sit-to-stand cycle, CR TKA knees demonstrated significantly lower knee valgus angles (-3.3 ± 2.6 vs. -7.1 ± 3.2 degrees; ►**Fig. 2B**), when compared with the nonoperated knee. CR TKA knees demonstrated significantly less medial femoral translation at 71 to 73% of the sit-to-stand cycle (-0.2 ± 3.3 vs. -2.5 ± 2.7 mm; ►**Fig. 2D**), when compared with the

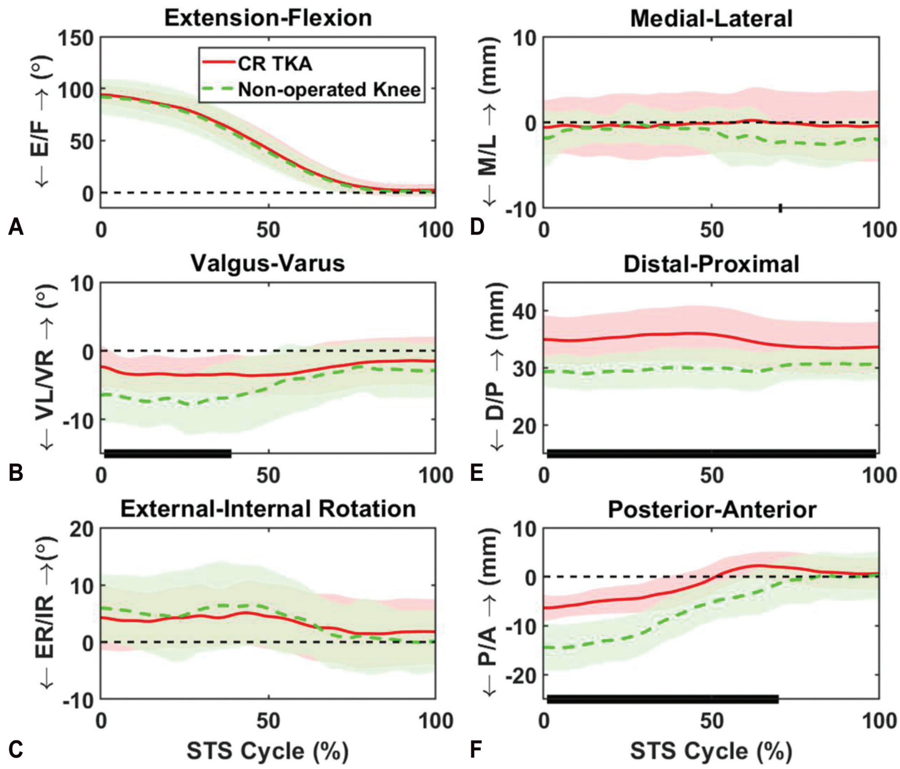

Fig. 2 Average and standard deviation of knee extension/flexion (**A**), knee valgus/varus (**B**), knee external/internal rotation (**C**), medial/lateral femoral translations (**D**), distal/proximal femoral translations (**E**), and posterior/anterior femoral translations (**F**) for the operated and nonoperated knees in unilateral cruciate retaining (CR) total knee arthroplasty (TKA) patients during sit-to-stand. Black bars on the horizontal axis (sit-to-stand cycle %) indicate statistical significant differences between limbs.

nonoperated knee. CR TKA knees demonstrated significantly larger proximal femoral translations than the nonoperated knee throughout the entire sit-to-stand cycle (34.7 ± 4.5 vs. 29.9 ± 3.1 mm; ►**Fig. 2E**).

There are no significant differences in knee flexion/extension between asymmetrical tibial polyethylene bearing geometry CR TKA and the native knee during step-ups (15.8 ± 6.4 vs. 14.7 ± 7.1 degrees; ►**Fig. 3A**). Asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated significantly less internal tibial rotation during the initial phase of the step-up cycle at 0 to 32% (2.6 ± 5.8 vs. 6.3 ± 6.6 degrees; ►**Fig. 3C**), when compared with the native knee. Significant differences in medial/lateral femoral translations were observed between CR TKA and the native knee during 47 to 59% of the step-up cycle (-0.5 ± 3.7 vs. -3.6 ± 3.1 mm; ►**Fig. 3D**). CR TKA knees demonstrated significantly lower posterior femoral translations for the first 65% of the step-up cycle (2.2 ± 3.2 vs. -3.5 ± 4.5 mm; ►**Fig. 3F**), when compared with the healthy knee.

Asymmetrical tibial polyethylene bearing geometry CR TKA knees demonstrated significantly larger knee flexion angles during late stance phase (9.2 ± 6.7 vs. 7.3 ± 8.6 degrees; ►**Fig. 4A**) and early swing phase (23.7 ± 11.6 vs. 19.4 ± 16.6 degrees; ►**Fig. 4A**), when compared with the nonoperated knee. CR TKA knees demonstrated significantly lower knee valgus angles during swing phase at 78 to 92% of the gait cycle (-3.9 ± 2.7 vs. -6.2 ± 4.8 degrees; ►**Fig. 4B**), when compared with the native knee.

Asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated significantly smaller knee flexion angles (92.3 ± 5.5 vs. 98.4 ± 8.1 degrees; ►**Fig. 5C**) at 68 to 100% of the single-leg deep lunge cycle, when compared with the nonoperated knee. From 54 to 100% of the single-leg deep lunge cycle, asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated significantly lower knee valgus angles (-3.1 ± 2.4 vs. -6.7 ± 3.4 degrees; ►**Fig. 5B**), when compared with the nonoperated knee. There was no significant difference in medial/lateral translation between asymmetrical tibial polyethylene bearing geometry CR TKA and the nonoperated knee during single-leg deep lunges (-0.8 ± 3.8 vs. -2.1 ± 2.5 mm; ►**Fig. 5D**). Significantly lower posterior femoral translations for the majority of lunge cycle (-2.5 ± 2.9 vs. -8.1 ± 4.4 mm; ►**Fig. 5F**) were observed for asymmetrical tibial polyethylene bearing geometry CR TKA knees, when compared with the nonoperated knee.

Range of Motion

The average range of extension/flexion motion did not differ significantly between CR TKA and the nonoperated knee during sit-to-stand (92.2 ± 7.7 vs. 91.4 ± 17.5 degrees, $p = 0.88$; ►**Table 2**). In knee valgus/varus, CR TKA had significantly less ROM than the healthy knee during sit-to-stand (5.3 ± 1.7 vs. 9.2 ± 3.1 degrees, $p = 0.0003$; ►**Table 2**). In external/internal rotation, asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated a significantly lower ROM, when compared with the native knee, during sit-to-stand (8.1 ± 2.6 vs. 14.0 ± 3.2 degrees, $p = 0.002$; ►**Table 2**). In

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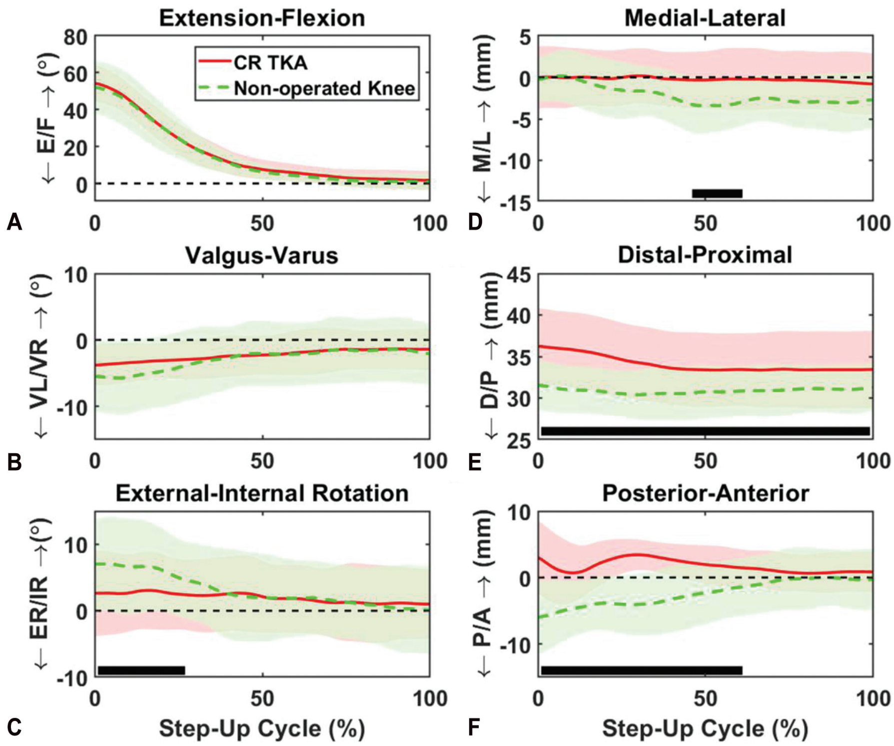

Fig. 3 Average and standard deviation of knee extension/flexion (**A**), knee valgus/varus (**B**), knee external/internal rotation (**C**), medial/lateral femoral translations (**D**), distal/proximal femoral translations (**E**), and posterior/anterior femoral translations (**F**) for the operated and nonoperated knees in unilateral cruciate retaining (CR) total knee arthroplasty (TKA) patients during step-ups. Black bars on the horizontal axis (step-up cycle %) indicate statistical significant differences between limbs.

addition, CR TKA had significantly less medial/lateral femoral translation than the healthy knee during sit-to-stand (10.3 ± 2.9 vs. 16.9 ± 6.1 mm, $p < 0.0001$; ►**Table 2**).

The average range of extension/flexion motion did not differ significantly between CR TKA and the nonoperated knee during step-ups (53.0 ± 9.5 vs. 51.9 ± 12.9 degrees, $p = 0.80$; ►**Table 3**). In knee valgus/varus, CR TKA had significantly less ROM than the healthy knee during step-ups (3.6 ± 1.5 vs. 6.3 ± 3.2 degrees, $p = 0.008$; ►**Table 3**). In external/internal rotation, asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated a significantly lower ROM, when compared with the native knee, during step-ups (8.2 ± 3.6 vs. 11.3 ± 3.7 degrees, $p = 0.03$; ►**Table 3**).

The average range of extension/flexion motion did not differ significantly between CR TKA and the nonoperated knee during gait (56.8 ± 8.1 vs. 59.2 ± 11.1 degrees, $p = 0.63$; ►**Table 4**). In external/internal rotation, asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated a significantly lower ROM during sit-to-stand (10.8 ± 4.3 vs. 17.5 ± 5.4 degrees, $p = 0.002$; ►**Table 4**), when compared with the native knee.

The average range of extension/flexion motion did not differ significantly between CR TKA and the nonoperated knee during single-leg deep lunge (97.3 ± 8.3 vs. 101.4 ± 11.2 degrees, $p = 0.76$; ►**Table 5**). In knee valgus/varus, CR TKA had significantly less ROM than the healthy knee during single-leg deep lunge (3.4 ± 1.9 vs. 6.1 ± 3.2 degrees, $p = 0.004$; ►**Table 5**). In external/internal rotation, asymmetrical tibial polyethylene bearing geometry CR TKA demonstrated a significantly lower ROM, when compared with the native knee, during single-leg deep lunge (5.0 ± 2.1 vs. 8.3 ± 2.9 degrees, $p = 0.03$; ►**Table 5**). In posterior/anterior femoral translation, asymmetrical tibial polyethylene bearing geometry CR TKA had significantly less ROM than the healthy knee during single-leg deep lunge (5.9 ± 3.9 vs. 13.9 ± 5.7 mm, $p < 0.0001$; ►**Table 5**).

Discussion

This is one of the first studies to investigate the in vivo knee kinematics in unilateral patients with the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design during gait and strenuous flexion activities. Asymmetric knee motions were observed between the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design and the native knee. In this cohort of patients, the contemporary CR TKA demonstrated significantly larger proximal femoral translations as well as significantly smaller posterior femoral translations than the native knee. Additionally, significantly smaller valgus and internal knee rotation angles were observed for the contemporary CR TKA design. These rotational and translational asymmetries of asymmetrical tibial polyethylene bearing geometry CR TKA with respect to the healthy knee were accompanied by significant loss in ROM for varus/valgus and external/internal knee rotation as well as anterior/posterior femoral translation gait and strenuous flexion activities.

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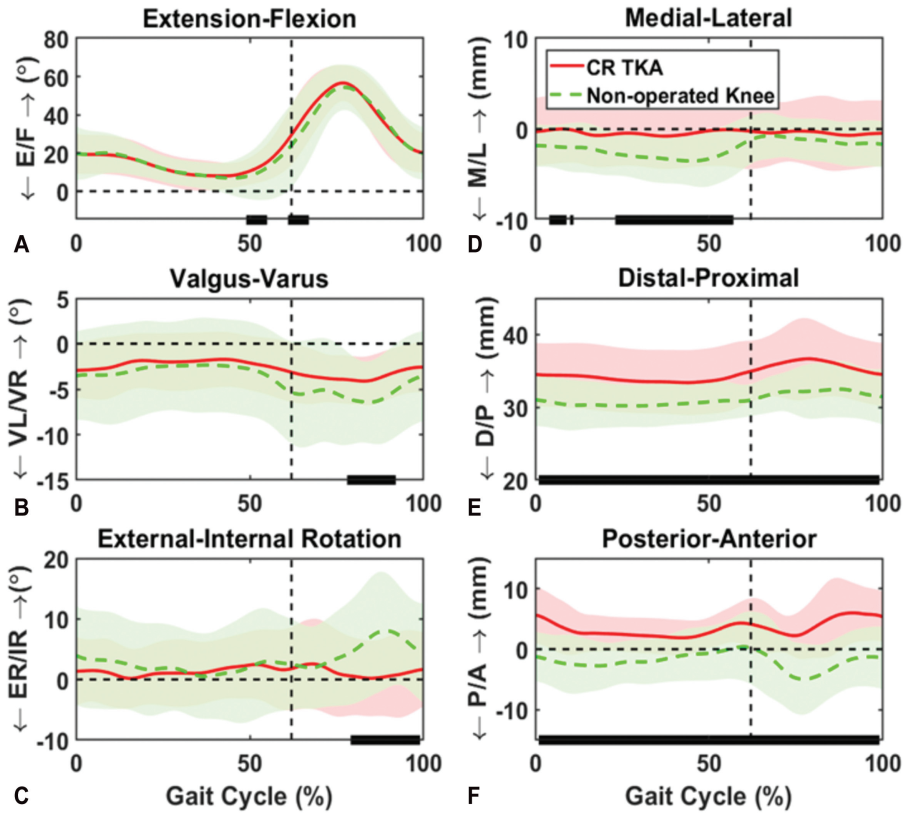

Fig. 4 Average and standard deviation of knee extension/flexion (**A**), knee valgus/varus (**B**), knee external/internal rotation (**C**), medial/lateral femoral translations (**D**), distal/proximal femoral translations (**E**), and posterior/anterior femoral translations (**F**) for the operated and nonoperated knees in unilateral cruciate retaining (CR) total knee arthroplasty (TKA) patients during gait. Black bars on the horizontal axis (gait cycle %) indicate statistical significant differences between limbs.

The CR TKA was designed to preserve the PCL with the aim of restoring native knee kinematics and enhancing proprioceptive feedback and ROM. However, the current study demonstrated 3D motion asymmetry of the knee in unilateral asymmetrical tibial polyethylene bearing geometry CR TKA patients during strenuous flexion activities and gait, relative to the contralateral native knee. The contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design demonstrated significantly smaller internal knee rotation angles during step-ups and gait than the healthy knee. This is in agreement with the study by Dennis et al,[24] demonstrating that previous CR TKA designs were unable to reproduce normal knee internal tibial rotation during deep knee flexion, with an average internal tibial rotation of 3.9 degrees when compared with 16.5 degrees of internal tibial rotation for the native knee. Similarly, Lee et al[25] demonstrated a significantly smaller external/internal rotation ROM between previous generation CR TKA designs and the healthy knee (6.1 ± 4.6 vs. 13.6 ± 6.9 degrees). While the trend of reduced internal tibial rotation in CR TKA than the native knee is similar across studies reported in the literature, the difference in absolute values could, in part, be attributed to different CR TKA designs as well as experimental methodologies and protocols. Beside discrepancies in internal tibial rotation, the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design demonstrated significantly smaller valgus rotation angles than the healthy knee during sit-to-stand, single-leg deep lunge, and gait. This may be due to the addition of the convex lateral tibial component of the contemporary CR TKA design, which may tilt the tibia more varus as the knee progresses through knee flexion and attempts to pivot around the medial aspect of the tibial component.

Several studies have demonstrated that previous CR TKA designs exhibited paradoxical femoral rollback which resulted in decreased weight-bearing flexion angles during functional daily activities.[26–28] The results in this study illustrated that there are no differences in knee flexion/extension ROM between the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design and the native knee during strenuous knee flexion activities as well as gait. This suggests that the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design in combination with the PCL supports posterior femoral translations at high knee flexion angles to increase the flexion ROM and to replicate healthy knee flexion/extension kinematics. The ability of CR TKA design to restore the normal flexion ROM is essential for a variety of functional daily activities[29] and failure to perform those daily tasks has resulted in patient dissatisfaction.[16]

The contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design demonstrated significantly smaller medial and posterior femoral translations than the native knee during strenuous knee flexion activities as well

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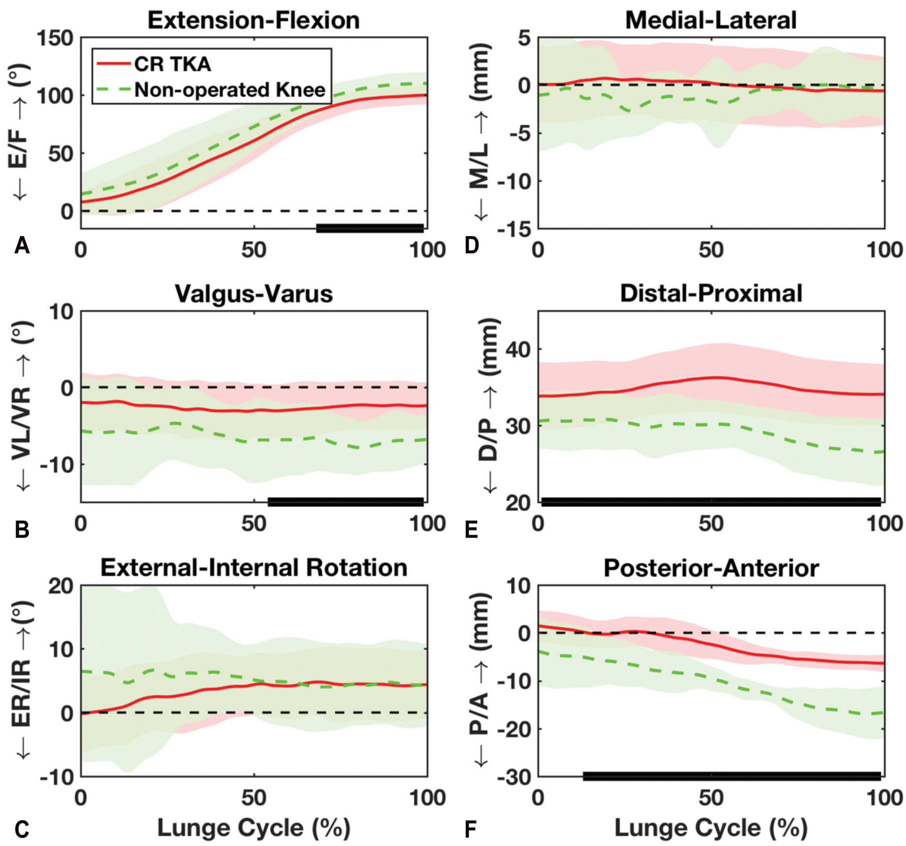

Fig. 5 Average and standard deviation of knee extension/flexion (**A**), knee valgus/varus (**B**), knee external/internal rotation (**C**), medial/lateral femoral translations (**D**), distal/proximal femoral translations (**E**), and posterior/anterior femoral translations (**F**) for the operated and nonoperated knees in unilateral cruciate retaining (CR) total knee arthroplasty (TKA) patients during single-leg deep lunge. Black bars on the horizontal axis (lunge cycle %) indicate statistical significant differences between limbs.

as gait. Despite the addition of a convex lateral tibial polyethylene bearing component in the contemporary CR TKA design to aid femoral posterior rollback during deep knee flexion, asymmetrical tibial polyethylene bearing geometry CR TKA was not able to achieve similar posterior femoral translations to the healthy knee. Similar findings have been presented in the literature with different CR TKA designs.[14,26,30] In addition to discrepancies in medial and posterior femoral translation, the contemporary asymmetrical tibial polyethylene bearing geometry CR TKA design

Table 2 Range of motion (ROM) of knee rotations and translations along different directions between CR TKA and native knees during sit-to-stand

Motion	Side	Avg	SD	Min	Max	*p*-Value
E/F ROM (degrees)	TKA Native	92.2 91.4	7.7 17.5	72.6 41.1	101.5 105.2	0.88
VL/VR ROM (degrees)	TKA Native	5.3 9.2	1.7 3.1	3.3 3.1	9.1 13.5	0.0003
ER/IR ROM (degrees)	TKA Native	8.1 14.0	2.6 3.2	3.7 6.4	14.8 27.5	0.002
M/L ROM (mm)	TKA Native	10.3 16.9	2.9 6.1	3.1 7.6	15.5 25.4	< 0.0001
D/P ROM (mm)	TKA native	3.5 4.9	0.6 2.1	2.4 2.6	4.8 8.0	0.038
P/A ROM (mm)	TKA Native	3.9 7.7	0.7 2.8	1.6 2.9	5.2 8.9	< 0.0001

Abbreviations: Avg, average; CR, cruciate retaining; Max, maximum; Min, minimum; SD, standard deviation; TKA, total knee arthroplasty.
Note: The range of femoral translations along lateral/medial (L/M), distal/proximal (D/P), and posterior/anterior (P/A) directions were reported. Avg), SD, Min, and Max across subjects were calculated. The Wilcoxon paired signed-rank test was performed to assess statistical significance.

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Table 3 Range of motion (ROM) of knee rotations and translations along different directions between CR TKA and native knees during step-ups

Motion	Side	Avg	SD	Min	Max	*p*-Value
E/F ROM (degrees)	TKA	53.0	9.5	34.4	66.0	0.80
	Native	51.9	12.9	24.0	71.8	
VL/VR ROM (degrees)	TKA	3.6	1.5	1.7	8.0	0.008
	Native	6.3	3.2	2.6	12.2	
ER/IR ROM (degrees)	TKA	8.2	3.6	2.3	14.9	0.03
	Native	11.3	3.7	4.5	17.0	
M/L ROM (mm)	TKA	6.9	2.1	2.9	10.7	0.19
	Native	8.3	3.5	3.4	14.3	
D/P ROM (mm)	TKA	3.4	1.0	1.6	5.2	0.18
	Native	2.8	1.2	1.2	4.9	
P/A ROM (mm)	TKA	3.8	0.9	1.2	5.4	< 0.0001
	Native	6.9	1.5	3.0	8.1	

Abbreviations: Avg, average; CR, cruciate retaining; Max, maximum; Min, minimum; SD, standard deviation; TKA, total knee arthroplasty.
Note: The range of femoral translations along lateral/medial (L/M), distal/proximal (D/P), and posterior/anterior (P/A) directions were reported. Avg, SD, Min, and Max across subjects were calculated. The Wilcoxon paired signed-rank test was performed to assess statistical significance.

demonstrated an asymmetry in distal/proximal femoral translation throughout the entire sit-to-stand, step-up, single-leg deep lunge, and gait cycle. This may suggest that this discrepancy is independent of flexion/extension. These differences in distal/proximal femoral translation may particularly impact the younger patient group, which has increasing functional demands and the failure to restore native knee kinematics has resulted in patient dissatisfaction.[16]

The study findings need to be interpreted in light of several potential limitations. First, the patients performed treadmill gait under DFIS surveillance at self-selected speed for safety reasons. The knee motion during treadmill gait may differ from level walking on the ground; however, previous studies have demonstrated similarities in knee kinematics between normal ground walking and treadmill walking.[31] Second, all patients in the current study had a single CR TKA design with an average of 24.5 months' follow-up time. Therefore, the findings of this study may not be generalized to different types of CR TKA systems. Additionally, the contralateral nonimplanted knee was used as control to evaluate unilateral CR TKA patients during strenuous knee flexion activities. However, all participants in this study presented no radiographic signs of OA in the contralateral nonoperated knee, and they were able to perform the sit-to-stand and step-up activities without any pain or assistance. Fourth, symmetric geometry between the left and right femur was assumed to map the coordinate system. However, patients with femoral and tibial deformities were excluded in this study. Finally, the study uses a variable follow-up time range (range 13–42 months) for assessment of testing in vivo kinematics. We acknowledge the study being performed at a similar follow-up time frame for all patients would be more ideal.[6,32,33] The present study was unfortunately limited by the availability of patients for participation in the in vivo kinematic investigation. In addition, this study did not

Table 4 Range of motion (ROM) of knee rotations and translations along different directions between CR TKA and native knees during gait

Motion	Side	Avg	SD	Min	Max	*p*-Value
E/F ROM (degrees)	TKA	56.8	8.1	39.6	65.7	0.63
	Native	59.2	11.1	45.2	79.5	
VL/VR ROM (degrees)	TKA	4.8	2.2	1.9	11.5	< 0.0001
	Native	9.2	2.6	5.3	13.9	
ER/IR ROM (degrees)	TKA	10.8	4.3	4.7	23.8	0.002
	Native	17.5	5.4	9.3	30.9	
M/L ROM (mm)	TKA	11.2	6.2	5.1	24.0	0.72
	Native	11.9	5.3	4.8	26.2	
D/P ROM (mm)	TKA	5.1	2.8	2.1	14.4	0.47
	Native	5.7	2.1	2.7	10.0	
P/A ROM (mm)	TKA	4.2	1.8	1.5	8.2	0.02
	Native	11.9	5.3	3.4	10.8	

Abbreviations: Avg, average; CR, cruciate retaining; Max, maximum; Min, minimum; SD, standard deviation; TKA, total knee arthroplasty.
Note: The range of femoral translations along lateral/medial (L/M), distal/proximal (D/P), and posterior/anterior (P/A) directions were reported. Avg, SD, Min, and Max across subjects were calculated. The Wilcoxon paired signed-rank test was performed to assess statistical significance.

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Table 5 Range of motion (ROM) of knee rotations and translations along different directions between CR TKA and native knees during single-leg deep lunges

Motion	Side	Avg	SD	Min	Max		*p*-Value
E/F ROM (degrees)	TKA Native	97.3 101.4	8.3 11.2	16.8 19.0	108.7 109.5		0.76
VL/VR ROM (degrees)	TKA Native	3.4 6.1	1.9 3.2	2.6 4.9	4.0 7.5		0.004
ER/IR ROM (degrees)	TKA Native	5.0 8.3	2.1 2.9	0.2 6.2	8.8 9.7		0.03
M/L ROM (mm)	TKA Native	8.3 12.7	2.4 5.2	4.2 7.3	11.9 27.7		< 0.0001
D/P ROM (mm)	TKA Native	4.2 5.8	1.3 2.7	2.5 3.1	6.0 8.7		0.04
P/A ROM (mm)	TKA Native	5.9 13.9	3.9 5.7	2.2 9.9	8.0 18.2		< 0.0001

Abbreviations: Avg, average; CR, cruciate retaining; Max, maximum; Min, minimum; SD, standard deviation; TKA, total knee arthroplasty.
Note: The range of femoral translations along lateral/medial (L/M), distal/proximal (D/P), and posterior/anterior (P/A) directions were reported. Avg, SD, Min, and Max across subjects were calculated. The Wilcoxon paired signed-rank test was performed to assess statistical significance.

have a full length radiograph to confirm whether there is an alignment difference between the knees that impact the study findings. However, this is a common limitation of similar studies.[5,6] Furthermore, this study did not assess other joints (hip, ankle, spine) that may have an impact on gait. However, this represents a common limitation of studies on this research.[34,35]

In conclusion, despite the replication of native knee flexion/extension by the contemporary asymmetrical bearing geometry CR TKA design with concave medial and convex lateral tibial polyethylene bearing components, asymmetric knee motion persisted in in vivo unilateral CR TKA patients during strenuous knee flexion activities and gait. Further studies are required to investigate the potential effects of implant designs, component positioning, and patient factors in optimizing in vivo kinematics of CR TKA during gait and functional daily activities.

Conflict of Interest
None declared.

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