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Comparing in vivo kinematics of unicondylar and bi-unicondylar knee replacements

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Abstract Preserving both cruciate ligaments in unicondylar knee arthroplasty likely provides more normal knee mechanics and contributes to enhanced patient function. It follows that preserving both cruciate ligaments with total knee arthroplasty should provide functional benefit compared to arthroplasty sacrificing one or both cruciates. The purpose of this study was to compare knee kinematics in patients with optimally functioning cruciate-preserving medial unicondylar and bi-unicondylar arthroplasty to determine if knee motions differed. Eight consenting patients with seven medial unicondylar and five bi-unicondylar arthroplasties were studied using lateral fluoroscopy during treadmill gait, stair stepping, and maximum flexion activities. Patient-specific geometric models based on CT and CAD data were used for shape matching to determine the three-dimensional knee kinematics. Tibiofemoral contact locations were computed for the replaced compartments. Maximum flexion in kneeling was 135° ± 14° for unicondylar knees and 123° ± 14° for bi-unicondylar knees ($p = 0.22$). For 0°–30° flexion during the stair activity, the medial condyle translated posterior 3.5 ± 2.5 mm in unicondylar knees and 4.7 ± 1.9 mm in bi-unicondylar knees ($p > 0.05$). Lateral posterior translation was 5.0 ± 2.3 mm in bi-unicondylar knees for 0°–30° flexion. From heel-strike to mid-stance phase, there was little tibial rotation, but unicondylar knees showed 1.5 ± 1.6 mm posterior translation of the medial condyle, while bi-unicondylar knees showed 5.1 ± 2.2 mm ($p < < 0.05$). The bi-unicondylar knees showed 3.8 ± 3.4 mm posterior lateral condylar translation. Preserving both cruciate ligaments in knee arthroplasty appears to maintain some basic features of normal knee kinematics. Knees with bi-unicondylar arthroplasty showed kinematics closer to motions observed in total knee arthroplasty, slightly less weight-bearing flexion, and greater dynamic laxity in gait than unicondylar knees. Despite kinematic differences, knees with unicondylar and bi-unicondylar arthroplasty can provide excellent functional outcomes in appropriately selected patients.

Keywords Knee arthroplasty · Kinematics · Fluoroscopy · Unicondylar knee replacement · Gait

Introduction

The results of unicondylar knee arthroplasties have improved steadily since their introduction over 30 years ago [1]. Improved designs, materials, and surgical techniques have played a role in improving outcomes, as have the development of more specific indications for their use. Current consensus suggests that the anterior cruciate ligament ought to be intact and fully maintained for most unicondylar knee arthroplasties, based on studies reporting greater implant survivorship [2–5], better gait mechanics [6], and more normal knee kinematics [7]. Similarly, outcome and kinematic studies suggest that maintaining the anterior cruciate ligament in bi- and tri-compartmental knee arthroplasty may be advantageous in terms of survivorship [8, 9], stair-climbing ability [10], patient satisfaction [11] and joint kinematics [12, 13].

What is not clear from these studies is how much knee kinematics might differ between the common medial unicondylar knee arthroplasty and a bi-unicondylar knee arthroplasty, where both cruciates are retained. Bi-unicondylar arthroplasty has shown good outcomes [8] and there is renewed interest in this technique with the increasing popularity of unicondylar arthroplasty and minimally invasive surgical techniques. Presumably, the bi-unicondylar arthroplasty will have greater intrinsic laxity after bicompartmental disease and loss of the normal lateral compartment, but may still show more normal knee motions guided by the retained cruciates. The goal of this study was to compare in vivo knee motions in patients with optimally performing unicondylar and bi-unicondylar knee arthroplasty for several weight-bearing activities.

Material and methods

Eight consenting patients with seven medial unicondylar and five bi-unicondylar arthroplasties participated in this Institutional Review Board approved study (Table 1). Patients were recruited for participation based on combined Knee Society scores greater than 195 [14] at minimum 8 months after surgery, return to high levels of activity post-arthroplasty, high satisfaction with the procedure and outcome, and willingness to drive up to 4 h to participate in the study. All patients underwent surgery by a single surgeon (S.R.) using a cemented metal-backed fixed-bearing tibial baseplate and cemented cobalt–chrome femoral prosthesis (Allegretto, Zimmer Inc, Winterthur, Switzerland). The surgical technique fully maintained both cruciate ligaments and replicated as closely as possible the normal articular surfaces and posterior slope of each tibial plateau. Tibial prostheses were implanted in 2°–3° varus with respect to the tibial mechanical axis. Femoral prostheses were positioned perpendicular to the tibial implants with resurfacing bone preparation. The medial and lateral femoral components were lateralized slightly to maintain contact on the center of the tibial bearing surface with flexion and endo/exorotation.

Patients' knee motions were recorded using lateral fluoroscopy during treadmill gait at 1 m/s, single limb stepping up and down on a 25-cm stair, maximum flexion in a lunge with the foot placed on the 25-cm step, maximum flexion kneeling on a padded stool, and weight-bearing straight-leg stance. The images were recorded on digital videotape at 30 frames per second for gait and 10 frames per second for all other activities. The digitized images were corrected for optical distortion using bilinear interpolation [15]. The Canny edge detector was used to identify bone and implant boundaries [16].

Image matching-based measurements of knee arthroplasty kinematics typically utilize surface models of the implanted metal components. Since the tibial components of this unicondylar system had only a thin metal wafer base and two small beads within the polyethylene, it was determined that a shape model incorporating implant and bone geometry would permit better measurement sensitivity and robustness for large out-of-plane motions. These models were created in a

Table 1 Characteristics of knee replacement patients

Sex	Age (years)	Weight (kg)	Right knee	Right follow-up (months)	Left knee	Left follow-up (months)	Life style
M	42	75	Healthy		Bi-uni	26	Sports
F	55	65	Bi-uni	18	Healthy		Active
F	60	80	Bi-uni[a]	8	Uni	9	Long walk
M	73	78	Uni	10	Uni	10	Long walk
M	73	75	Bi-uni	21	Healthy		Sports
M	74	72	Uni	21	Uni	21	Sports
F	79	74	Uni	15	Uni	22	Long walk
M	79	65	Uni[b]		Bi-uni	36	Active

[a]Total knee replacement femoral component used with bi-unicondylar tibial components
[b]Well-functioning unicondylar knee, but no CT data to permit inclusion in study

five-step process: (1) CT data were collected from the implanted limb of each patient using a Siemens Somatom Plus 4 scanner with fine scans around the knee region and single slices at the hip center and ankle center. The fine scan parameters included 3 mm slice thickness, 512×512 image matrix, and between a 250×250 mm and a 490×490 mm field of view depending on whether one leg was scanned or two. (2) External cortical bone surfaces of the femur, tibia, fibula, and patella (Fig. 1a) were segmented semi-automatically using a watershed algorithm, while the metallic implant components were segmented manually (SliceOmatic, Tomovision, Montreal, Canada). (3) Polygonal bone surface models were created from the segmented points defining their boundaries using commercial reverse engineering software (Geomagic Studio, Raindrop Geomagic, Research Triangle Park, NC, USA; Fig. 1b). Bone was not reconstructed in the area directly adjacent to the implanted components. (4) Manufacturer-supplied implant models were registered with their segmented outlines using a three-dimensional automatic alignment routine (Geomagic Studio; Fig. 1c). The segmented points corresponding to the metallic implant components were then removed to produce a final composite bone-implant model (Fig. 1d). (5) Finally, coordinate systems were fixed in each bone-implant model. Femoral models were aligned so that the superior/inferior axis connected the hip center and knee center and the medial/lateral axis connected the epicondyles. Tibia/fibula models were aligned so that the superior/inferior axis connected the tibial plateau center and ankle center and the anterior/posterior axis intersected the medial third of the tibial tubercle. The sagittal slope of each tibial component relative to the long axis of the segment was measured.

The three-dimensional position and orientation of the proximal and distal knee segments was determined using a toolbox of model-based shape-matching techniques, including previously reported techniques [15], manual matching, and automated matching using nonlinear least-squares (modified Levenberg–Marquardt) techniques (Fig. 2). A total of 3,211 fluoroscopic images, an average of 268 images per knee, were analyzed. The optical geometry of the fluoroscopy system (principal distance, principal point) was determined from images of a calibration target [15]. The implant surface model was projected onto the geometry corrected image, and its three-dimensional pose was iteratively adjusted to match its silhouette with the silhouette of the subject's knee components and bones. The results of this shape-matching process have standard errors of approximately 0.5°–1.0° for rotations and 0.5–1.0 mm for translations in the sagittal plane [15].

Joint kinematics were determined from the three-dimensional pose of each knee component using Cardan/Euler angles [17]. The anterior/posterior locations of the tibiofemoral contact were computed, independently for each implanted compartment, by transforming the joint pose into a reference system parallel to the transverse plane of the flat tibial component and finding the lowest point on the femoral component.

For the stair, kneeling, and lunge activities, kinematics were expressed relative to the joint pose in straight-leg weight-bearing stance. For gait, the kinematics were expressed relative to the joint pose at heel-strike. Kneeling and lunge data were compared using *t* tests. For the stair and gait data, an average curve for each knee was created from four trials of data. These average curves were then combined to create group averages. Statistical comparisons for the gait and step

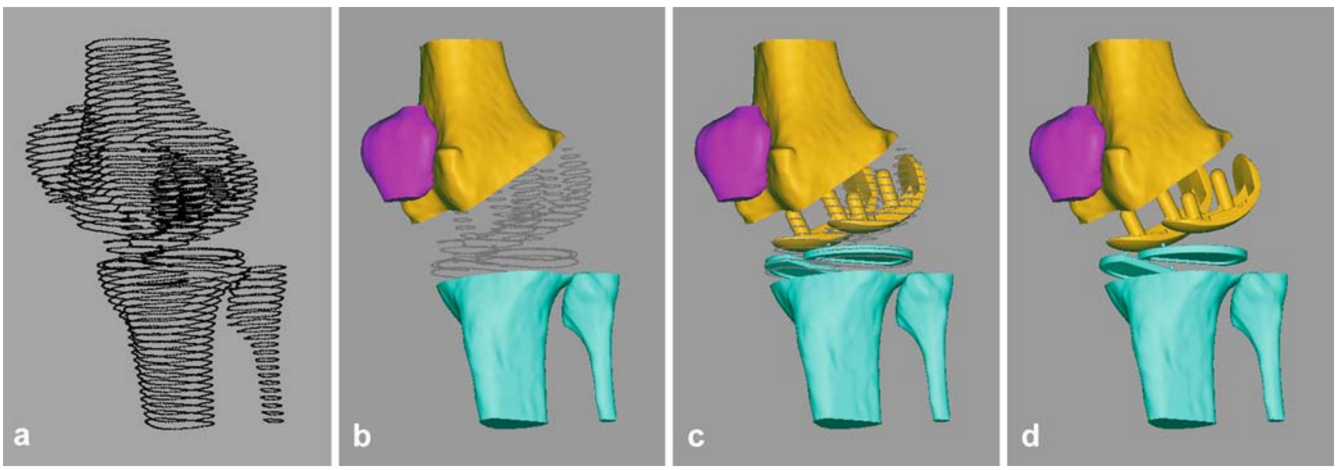

Fig. 1 Patient-specific shape models for image matching were created from a composite of bone and implant geometry. Bone surfaces were reconstructed from CT scans (**a, b**). Implant CAD models were registered with their CT outlines (**c**), and the CT outlines were removed leaving the final shape model (**d**)

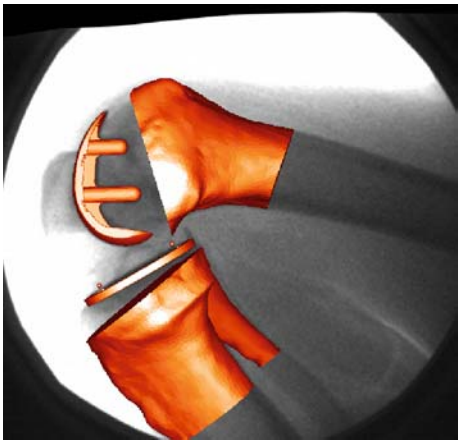

Fig. 2 Three-dimensional pose measurements for the femur and tibia/fibula segments were accomplished by projecting the shape models onto the digitized and distortion-corrected fluoroscopic images. The model pose was varied until the projected shapes matched those in the image

data were performed using a two-factor, repeated-measures analysis of variance (ANOVA) with post-hoc pair-wise comparisons (Tukey's honestly significant difference). The level of significance was set at $p \leq 0.05$.

Results

Maximum knee flexion in kneeling and lunge was an average of 10° greater ($p > 0.22$) for unicondylar knees at 135°/133° (Table 2). Average tibial internal rotation was greater in the unicondylar knees for kneeling ($p = 0.18$) and lunge ($p = 0.06$) activities. None of these differences was statistically significant. Posterior translation of the medial condyle averaged 2 mm or less for both types of knees in the lunge and kneeling activities. Posterior translation of the lateral condyle in the bi-unicondylar knees averaged 4 mm for the lunge and kneeling activities.

Both groups of knees showed tibial internal rotation with flexion during the stair activity (Fig. 3). The unicondylar knees showed greater tibial rotation for flexion from 20° to 80° ($p < < 0.01$). For 0°–30° flexion during the stair activity, the medial condyle translated posterior 3.5 ± 2.5 mm in unicondylar knees and 4.7 ± 1.9 mm in bi-unicondylar knees ($p = 0.035$). Lateral condyle posterior translation was 5.0 ± 2.3 mm in bi-unicondylar knees for 0°–30° flexion.

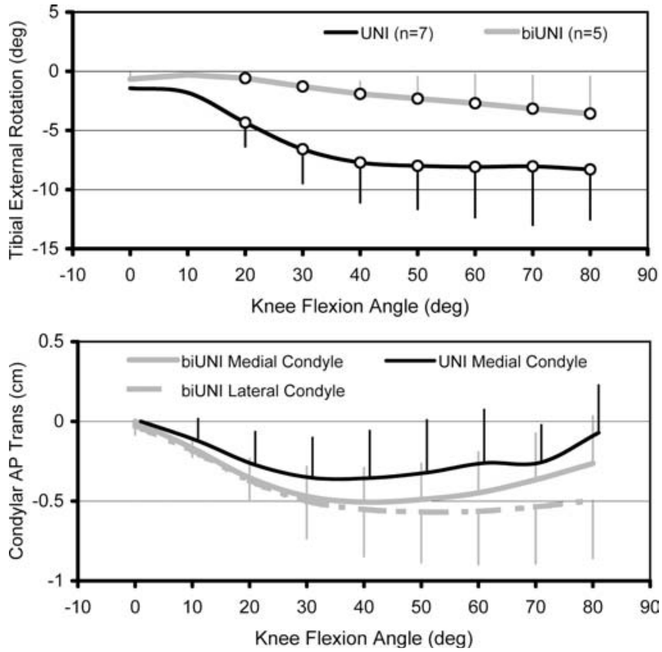

Fig. 3 The pattern of tibial rotation (mean ± 1 standard deviation) for unicondylar and bi-unicondylar knees differed ($p < < 0.001$) during the stair activity (*top*). Medial condyle AP translations also differed ($p = 0.035$), but there were no statistically significant differences for specific flexion ranges (*bottom*). AP translations for the medial and lateral condyles of the bi-unicondylar knees were the same from 0° to 40° flexion. The *white circles* indicate where there is a significant pair-wise difference between the two data series

The bi-unicondylar knees showed greater knee flexion from heel-strike to mid-stance phase than the unicondylar knees ($p < < 0.01$) but similar flexion from late stance through swing phase (Fig. 4a). The bi-unicondylar knees showed greater tibial external rotation throughout stance phase ($p < < 0.01$, Fig. 4b), which correlates closely to greater posterior translation of the medial condyle in early to mid stance phase ($p < < 0.01$,

Table 2 Knee kinematics in deep flexion kneeling and lunge postures (mean ± 1 standard deviation, range in parentheses)

Parameter	Kneeling		Lunge	
	Uni	Bi-uni	Uni	Bi-uni
Flexion (deg)	135 ± 14 (114 to 150)	123 ± 14 (108 to 136)	133 ± 15 (111 to 150)	124 ± 12 (107 to 135)
Axial rotation (deg)	9 ± 6 (3 to 19)	3 ± 7 (−3 to 13)	12 ± 7 (−1 to 19)	4 ± 6 (−2 to 12)
Medial rollback (mm)	2 ± 15 (−5 to 11)	0 ± 5 (−6 to 5)	2 ± 4 (−2 to 11)	1 ± 5 (−6 to 6)
Lateral rollback (mm)		4 ± 9 (−4 to 16)		3 ± 9 (−6 to 16)

There were no statiscally significant differences between Uni and Bi-uni knees

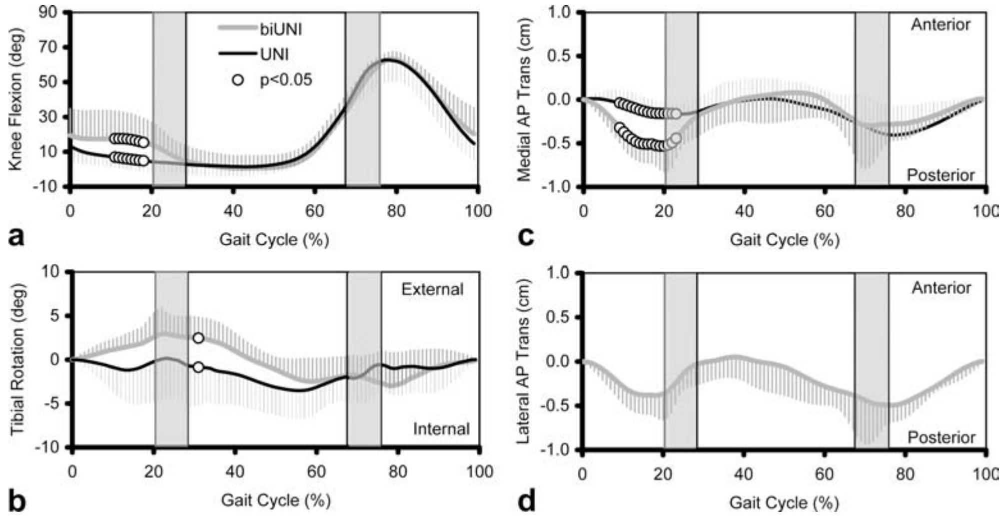

Fig. 4 Knee kinematics during gait differed between the unicondylar knees (*UNI*) and the bi-unicondylar knees (*biUNI*) (mean ± 1 standard deviation). The bi-unicondylar knees showed greater flexion in early stance, but similar flexion in late stance and swing (**a**). The bi-unicondylar knees showed greater tibial external rotation during stance (**b**). The bi-unicondylar knees showed significantly greater posterior translations of the medial condyle in early stance (**c**), and a similar pattern of AP motion for the lateral condyle (**d**). The two *gray regions* on each graph indicate gaps in the fluoroscopic data, when the contralateral knee occludes the view, which are filled by interpolation. The *white circles* indicate where there is a significant pair-wise difference between the two data series

Fig. 4c). Lateral condylar AP translations in the bi-unicondylar knees were similar in pattern, but smaller in magnitude, compared to the medial condylar translations (Fig. 4d).

Discussion

Well-performed contemporary knee arthroplasty provides excellent 10-year outcomes almost without regard to the particular philosophy or implant type utilized. In this context, the focus for improvement shifts to patients' functional abilities and limitations. Contemporary unicondylar knee arthroplasty is widely acknowledged to provide more normal postoperative function than total knee arthroplasty [6], and it is assumed that retaining both cruciates contributes to this functional advantage. It is natural, therefore, to ask whether bi-unicondylar knee arthroplasty might provide similar knee kinematics and function. This study attempts to answer that question for a highly selected small group of active patients with excellent outcomes.

This selected group of unicondylar and bi-unicondylar knees showed average maximum flexion that was equivalent to or better than previously has been reported for knee arthroplasty in Western patients [8, 9, 18–20]. These knees prove that excellent flexion can be achieved with these techniques, but it is likely that the mean maximum flexion would be less for a more broadly representative group of patients. Kinematics in both groups varied substantially between knees for the deep flexion activities, so that no statistically significant differences could be demonstrated (Table 2).

Posterior translation of the medial condyle with flexion was observed in both knee groups for the stair activity, 3.5 mm for the unicondylar and 5 mm for the bi-unicondylar knees. This finding is consistent with prior studies of anterior cruciate ligament retaining total knee arthroplasty [12, 13], but the translations were greater than reported in studies of medial unicondylar knee arthroplasty [7] or the healthy knee [21, 22] for quasi-static activities. It was particularly surprising in the bi-unicondylar knees that the medial and lateral condyles translated posteriorly the same amount in early flexion (0°–40°), again contrasting with reports of normal knee kinematics during quasi-static activities [21, 22].

The unicondylar knees showed less than 2 mm AP translation of the medial condyle during the stance phase of gait. The bi-unicondylar knees showed more than 5 mm posterior translation of the medial condyle just after heel-strike, indicating greater dynamic laxity. Two factors likely contributed to the increased medial condylar sliding: First, these knees had greater flexion in early stance phase, so the knees were in a position of increased passive laxity [23]. Second, the bi-unicondylar knees had bicompartmental disease preoperatively and no longer maintained the normal laxity of the lateral compartment post arthroplasty. As a result, the pattern of motion during gait in the bi-unicondylar knees was closer to motions reported for fixed-bearing total knee replacements in identical tests [24, 25].

As reported by others and confirmed in this study, preserving both cruciate ligaments in knee arthroplasty maintains some basic features of normal knee kinematics, including posterior translation of the femoral condyles and tibial internal rotation with flexion. These motions were most evident during the stair activity for the unicondylar and bi-unicondylar knees. As one might expect, the dynamic laxity of the knee increased when both tibiofemoral compartments were replaced, which was most apparent during gait.

In conclusion, the kinematics of unicondylar and bi-unicondylar knee arthroplasty share common features, but differ in ways that are consistent with the bicompartmental preoperative disease and loss of the normal lateral compartment in the bi-unicondylar knees. Despite kinematic differences compared to unicondylar knees, bi-unicondylar arthroplasty can provide functional outcomes similar to unicondylar knees in appropriately selected patients.

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