In vivo knee kinematics during high flexion after a posterior-substituting total knee arthroplasty

Angela L. Moynihan · Kartik M. Varadarajan · George R. Hanson · Sang-Eun Park ·
Kyung Wook Nha · Jeremy F. Suggs · Todd Johnson · Guoan Li

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Abstract The objective of this study was to investigate biomechanics of TKA patients during high flexion. Six patients (seven knees) with a posterior-substituting TKA and weight-bearing flexion $>130^\circ$ were included in the study. The six degree-of-freedom kinematics, tibiofemoral contact, and cam-post contact were measured during a deep knee bend using dual-plane fluoroscopy. The patients achieved average weight-bearing flexion of $139.5 \pm 4.5^\circ$.

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A. L. Moynihan · K. M. Varadarajan · G. R. Hanson ·
J. F. Suggs · G. Li (✉)
Department of Orthopaedic Surgery, Bioengineering Laboratory,
Massachusetts General Hospital and Harvard Medical School,
55 Fruit Street, GRJ 1215,
Boston, MA 02114, USA
e-mail: gli1@partners.org

S.-E. Park
Department of Orthopaedic Surgery,
Dongguk University International Hospital,
814, Siksa-dong, Ilsangong-gu, Goyang-si,
Gyeonggi-do Ilisan, South Korea 411-773

K. W. Nha
Department of Orthopaedic Surgery,
Inje University and Ilsanpaik Hospital,
Ilisan, South Korea

K. M. Varadarajan · J. F. Suggs
Department of Mechanical Engineering,
Massachusetts Institute of Technology,
Cambridge, MA, USA

T. Johnson
Zimmer Inc.,
P.O. Box 708, 1800 West Center Street,
Warsaw, IN 46581, USA

Posterior femoral translation and internal tibial rotation increased steadily beyond 90° flexion, and a sharp increase in varus rotation was noted at maximum flexion. Initial cam-post engagement was observed at $100.3 \pm 6.7^\circ$ flexion. Five knees had cam-post disengagement before maximum flexion. Lateral femoral condylar lift-off was found in five out of seven knees at maximum flexion, and medial condylar lift-off was found in one knee. Future studies should investigate if the kinematic characteristics of posterior-substituting TKA knees noted in this study are causative factors of high knee flexion.

Introduction

Achieving high flexion after total knee arthroplasty (TKA) has attracted much attention in clinical and basic science literature [2, 3, 6, 17, 21]. Typically the average range of weight bearing knee flexion following TKA is less than 120° [2, 24]. While this may be sufficient for performing most daily activities, activities such as gardening or kneeling, require greater knee flexion [22]. This is particularly important in Eastern cultures where high flexion activities, such as squatting and sitting cross-legged, are part of the normal lifestyle [12, 20, 22].

Numerous studies have examined TKA biomechanics in order to delineate the factors inhibiting knee flexion [3, 6]. Most of these studies have reported that following TKA the knee shows reduced magnitudes of posterior femoral translation and internal tibial rotation with flexion, compared to intact knees [5, 11, 16]. Recently, our laboratory investigated TKA and native knee kinematics for flexion up to 150° , using an in vitro robotic testing system [17]. Such studies have revealed TKA biomechanics from an in vitro perspective. However, the in vivo biomechanics of TKA

beyond 120° is still unclear. This information is critical for understanding what biomechanical characteristics are present after TKA at high flexion.

The objective of this study was to investigate the contact patterns and kinematics of posterior-stabilising TKA in patients who could achieve greater than 130° of knee flexion, using a dual fluoroscopic imaging system [11]. In addition to the six degree-of-freedom kinematics, the tibiofemoral contact locations in the medial and lateral compartment, cam-post engagement/disengagement and condylar lift-off were also examined.

Materials and methods

Eight female South Korean patients (12 knees) with end stage osteoarthritis of the knee were recruited from the practice of a single surgeon. All patients had a posterior-substituting TKA (LPS-Flex; Zimmer Inc., Warsaw, IN, USA). This TKA facilitates tibiofemoral articulation at high flexion via a design modification involving increased thickness of the posterior wall of the femoral component by 2 mm compared to standard NexGen LPS design. The purpose of this modification is to increase articular contact area at high flexion [17]. Additionally, the anterior margin of the tibial articular surface is recessed to prevent impingement of the extensor mechanism.

Patients had an average age of 70 years (range 60–74 years) and were at least six months postoperative. Initial selection criteria required each patient to achieve >120° of passive flexion six months postoperatively. After data collection, only patients achieving at least 130° of weight-bearing flexion were included in the study. The weight-bearing flexion for each patient was determined as the maximum flexion of the femoral component relative to the tibial component. Seven knees were included in the final analysis. Subject demographics are listed in Table 1. Prior to the study, Institutional Review Board approval from participating institutions and informed patient consent were obtained.

Table 1 Patient demographics

Demographic	Mean $\pm$ standard deviation
Age (y)	68.0 $\pm$ 4.1
Weight (kg)	65.2 $\pm$ 11.7
Height (cm)	157.2 $\pm$ 5.8
Passive range of motion (deg)	147.9 $\pm$ 7.6
Full extension (deg)	−9.5 $\pm$ 4.0
Maximum active flexion (deg)	139.5 $\pm$ 4.5
Active range of motion (deg)	148.0 $\pm$ 6.2

Images of the knee were taken using a dual fluoroscopic imaging system (BV Pulsera; Philips, Bothell, WA) while patients performed a deep knee bend [11, 19]. To facilitate maximum flexion, the leg of interest was elevated on a step (Fig. 1). The knee was imaged at 15° flexion increments from full extension to 90° flexion, and approximately 5° flexion increments beyond 90°. The fluoroscopic images of the knee and the computer models of the femoral and tibial TKA components were imported into a virtual environment (Rhinceros; McNeel, Seattle, WA) [11, 19]. The models were then matched to the fluoroscopic images to recreate the in vivo kinematics of the knee [11, 19].

Six degree-of-freedom kinematics were calculated from the matched positions of the TKA components, based on embedded coordinate systems [10, 25]. The flexion axis was defined by a line connecting the tips of the two femoral component pegs. Femoral translations were measured from the centre of the flexion axis. Varus-valgus rotation was measured as the rotation of the flexion axis in the frontal plane; internal-external rotation was defined as rotation of the tibia about an axis perpendicular to the flexion axis and the tibial plateau surface [10, 25].

Tibiofemoral contact location was calculated by finding the overlapping area between the femoral and polyethylene surface models [19]. This included contact in the medial and lateral compartments, and between the femoral cam and tibial polyethylene post. The centroid of the contact area was used to represent the contact location. If no intersection between the components existed, then the femur was translated perpendicular to the tibial tray until an intersection point was found. Previous validation studies have shown the system resolution to be within 0.16 mm for the

Fig. 1 Patient positioning at maximum flexion during fluoroscopic imaging

femoral component and 0.13 mm for the tibial component [11, 19]. Therefore, if the translation distance was less than 0.29 mm, contact location was included; any greater distance was considered to be condylar lift-off. The articular contact locations were mapped onto the polyethylene surface using a local coordinate system for the medial and lateral compartments [10].

In this study, we have reported the average tibiofemoral contact kinematics, cam-post contact, and the six degree-of-freedom kinematics for the patients at different flexion angles between 0° and 120° and at maximal flexion. Individual patient data are included as supplementary material (Figs. A1–A5).

We were primarily interested in kinematics at high flexion in this study. Therefore, a one-way repeated ANOVA analysis was performed on all data, with flexion as the (repeated) independent factor and the kinematic parameter as the dependent variable. This analysis was done to compare knee kinematics at maximum flexion with those at flexion angles from 90° to 120°. The aim was to investigate how kinematics at maximum flexion differed from those at 90°, 105° and 120° flexion. The level for statistical significance was set as $p < 0.05$.

Results

Kinematics

Under weight bearing conditions, four of the seven knees reached flexion values greater than 142°, while one knee of one patient achieved maximum flexion of 133°. The average active and passive ranges of motion were similar for knees in this study (Table 1).

Anteroposterior translation data revealed that the femur moved in the anterior direction from 0° to 30° of flexion (Fig. 2). Beyond 30° of flexion, the femur travelled posterior until maximum flexion. Statistical analysis on

data from 90° to maximum flexion revealed that the femur was located significantly more posterior at maximum flexion than at 90°, 105° and 120° flexion ($p < 0.05$). On average the internal tibial rotation increased with knee flexion, although slight decrease was noted at 90° flexion (Fig. 3a). Statistical analysis on data from 90° to maximum flexion did not show any significant difference between tibial rotations at flexion angles above 90°. Varus rotations remained small through knee flexion from 0 to 120° (Fig. 3b). Beyond 90° flexion, varus rotation changed significantly with knee flexion, particularly from 120° to maximum flexion.

Femoral condylar lift off and cam-post engagement

At maximum flexion, tibiofemoral contact in the medial compartment was observed in six of the seven knees and tibiofemoral contact in the lateral compartment was observed only in two of the seven knees (Table 2). In general, tibiofemoral contact locations in the medial compartment were found in the medial and posterior portion of the polyethylene surface. Two out of the six instances of contact in the medial compartment at maximum flexion were observed to be close to the medial edge of the polyethylene and were considered slight contact. This indicated that the femoral component was close to lift-off in these cases. In the lateral compartment, the two instances of contact at maximum flexion approached the posterior edge of the polyethylene. Only one knee demonstrated contact in both compartments at maximum flexion (Table 2).

In all knees, cam-post engagement occurred at high flexion angles, beginning at approximately $100.3 \pm 6.7^\circ$ of flexion and ending at $127.4 \pm 12.7^\circ$ (Table 3). At maximum flexion, only two knees had contact between the femoral cam and polyethylene post. All others exhibited disengagement at maximum flexion (Fig. A5, supplementary material).

Fig. 2 Average posterior translation during flexion (* $p < 0.05$)

Fig. 3 Average internal (a) and varus (b) rotation during flexion (* $p<0.05$)

Articular contact kinematics

Tibiofemoral contact location in both the medial and lateral compartments showed posterior translation between 0° and

45° flexion, followed by anterior translation between 45° and 90° flexion. Beyond 90° flexion, medial and lateral contact points showed rapidly increasing posterior translation (Figs. 4a and b). Statistical analysis of data from 90° to

Table 2 Femoral compartment lift-off during active knee flexion

Patient	Max flexion (°)	Medial compartment			Lateral compartment		
		First lift-off seen (°)	Last lift-off seen (°)	Lift off at max flexion	First lift-off seen (°)	Last lift-off seen (°)	Lift off at max flexion
1R	142.9	125.3	125.3	N	142.9	142.9	Y
2R	132.7	None	None	N	125.8	132.7	Y
3R	136.7	None	None	N	123.5	136.7	Y
4L	143.1	135.4	135.4	N	142.4	143.1	Y
5L	142.1	None	None	N	142.1	142.1	Y
6L	135.5	133.2	133.2	N	115.0	126.7	N
6R	143.6	132.1	143.6	Y	None	None	N
Mean ± SD	139.5 ± 4.5	131.5 ± 4.3	134.4 ± 7.5	Y=1, N=6	131.9 ± 12.1	137.4 ± 6.7	Y=5, N=2

Y yes, N no, L left knee, R right knee, SD standard deviation

Table 3 Timing of cam-post contact during active knee flexion

Patient	Max flexion (°)	First post contact seen (°)	Last post contact seen (°)	Post contact at max flexion
1R	142.9	92.3	142.9	Y
2R	132.7	100.4	125.8	N
3R	136.7	99.7	136.7	Y
4 L	143.1	111.9	111.9	N
5 L	142.1	105.7	109.1	N
6 L	135.5	94.2	133.2	N
6R	143.6	97.9	132.1	N
Mean $\pm$ SD	139.5 $\pm$ 4.5	100.3 $\pm$ 6.7	127.4 $\pm$ 12.7	Y=2, N=5

Y yes, N no, L left knee, R right knee, SD standard deviation

maximum flexion showed that at maximum flexion the medial contact point was significantly more posterior than at 90°, 105° and 120° flexion.

Discussion

Although high flexion after TKA has been discussed previously, few studies have investigated kinematic patterns after TKA beyond 120° [4, 8, 10]. This study presented in vivo data regarding six degree-of-freedom kinematics, tibiofemoral contact patterns and condylar lift-off in

seven knees after TKA, with an average maximum flexion of ~140°.

The knees of patients in this study showed anterior femoral translation from full extension to 30° flexion, which was similar to the paradoxical motion often reported in the literature [5, 25]. Beyond 30°, the femur moved posteriorly with flexion. This was similar to previously reported in an in vitro study using a robotic testing system with the same posterior-substituting component [17].

On average, the internal tibial rotation was found to increase with flexion until 75° and then drop slightly at 90°. The internal rotation increased again with flexion beyond 90°. In another study, Suggs et al. [25] showed that internal tibial rotation increased up to 90° of flexion and decreased at 113° of flexion for a cohort of 17 South Korean TKA patients (24 knees). Both our study and a previous in vitro robotic study using cadaveric knees [17] demonstrated an increase in internal tibial rotation at maximum flexion. This has also been seen previously in normal subjects during a deep flexion squat activity [1].

Previous in vivo studies of human knees have shown an increase in varus rotation at higher flexion angles [10, 18]. The kinematics of normal knees in a recent study showed increasing varus rotation between 90° and 105° [18]. However, prior to our study, varus-valgus rotation of the knee after TKA at flexion greater than 120° was unknown. Our data indicated that the varus-valgus rotation remained relatively constant from full extension to 105°, and increased sharply at higher flexion angles (Fig. 3b) [10]. The increase in varus rotation at maximum flexion represents a kinematic characteristic of knees achieving high flexion that may help delineate the biomechanical factors that correlate to high-flexion capability in these patients.

The patterns of tibiofemoral contact locations below 90° flexion in the medial and lateral compartments were found to be similar to those reported in literature [10, 25]. For example, in both compartments, the contact location moved

Fig. 4 Graphical representation of the contact location in the anterior-posterior direction during knee flexion for medial (a) and lateral compartments (b) (* $p < 0.05$)

posteriorly with flexion up to 45° and then anteriorly to around 90°, followed by further posterior translation through maximum flexion.

In general, femoral condylar lift-off was observed only at or near maximum knee flexion. Prior studies have reported on condylar lift-off in posterior-substituting designs for both medial and lateral compartments during deep knee bend activities [7, 15, 23]. However, these studies reported data for flexion angles only up to 90° [7, 15, 23]. In addition, previous techniques have overlooked the contoured shape of the polyethylene [7, 15, 23]. In our study, contact measurement considered the 3D shape of the polyethylene component. Condylar lift-off was seen on the lateral side in five out of seven knees and in only one knee on the medial side at maximum flexion. This indicates that lateral condylar lift-off may occur frequently in patients achieving high flexion. These data agree with our previous study where, during a kneeling activity, 18 out of 22 knees had lateral condylar lift-off at an average maximum flexion of 128.0° [10]. This femoral condylar lift-off seen at maximal flexion may be a result of posterior soft tissue compression as discussed in the literature [10, 17, 25]. The increased varus rotation seen in this study at maximum flexion also supports the occurrence of lateral lift-off. Tibiofemoral lift-off has been an issue of concern with regards to polyethylene wear and component longevity [13]. In our study and that of Suggs et al. [25], condylar lift-off was only seen at high flexion, but these studies involved quasi-static knee bends. Future studies should further investigate the femoral condylar lift-off phenomenon during dynamic activities such as walking and stair climbing.

Little is known about cam-post contact patterns at high flexion in posterior-substituting TKA. In a recent study, Suggs et al. determined the initial cam-post engagement during weight bearing flexion to occur at ~90° flexion [25]. A modest correlation was also observed between the initial cam-post engagement angle and maximum flexion angle. In our study, cam-post engagement began around 100°, and the maximum flexion angle was ~140°. This result supports the observation of Suggs et al. [25] that a larger initial cam-post engagement angle may correspond to increase in maximum knee flexion. However, this observation may only apply to the TKA component investigated in this study.

On average, the cam-post engagement was last seen around 127°. Only two subjects had cam-post contact at maximum flexion indicating that cam-post disengagement can occur at high flexion angles. In a robotic in vitro study using the same posterior-substituting design, Li et al. observed cam-post disengagement at flexion angles greater than 135° as well as continued posterior femoral translation [17]. In our study continued posterior femoral translation also occurred at high flexion angles after cam-post disengagement. Compression of posterior soft tissue may

explain the cam-post disengagement at higher flexion angles.

Although the need for increased range of knee flexion has been widely recognised, there is also concern regarding the risk factors of high flexion including instability and implant loosening [9]. For example, Han et al. noted increased incidence of femoral component loosening at mean follow-up of 2.7 years in 47 South Korean patients with LPS-Flex TKA engaging in weight-bearing high-flexion activities [9]. However, results are not conclusive since other studies have shown favourable outcomes. For example, Kim et al. found a cumulative survival rate of 99.6% at 3.8 years for LPS-Flex TKA implanted in 187 South Korean patients [14].

Several limitations exist in our study. A single posterior-substituting TKA design was tested; therefore, the kinematic patterns reported may be specific to this design. Future studies should examine kinematics of other TKA designs. Additionally, the deep knee bend activity was studied in a quasi-static fashion. Therefore, the kinematics may not be the same as those during dynamic knee motion.

In conclusion, this study investigated the kinematics of patients with posterior-substituting TKA who could achieve an average weight-bearing knee flexion of ~140°. Continued posterior femoral translation and internal tibial rotation were observed at maximum flexion, as well as a sharp increase in varus rotation. Initial cam-post engagement was observed at 100° of flexion, followed by cam-post disengagement prior to maximum flexion. Lateral femoral condylar lift-off was also a common characteristic of patients who achieved high flexion. These data provide insight into the kinematic characteristics of the knee after a posterior-substituting TKA. Future studies should investigate if the kinematic features are causative factors of high knee flexion.

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Conflict of interest One of the coauthors is an employee of Zimmer, Inc. None of the coauthors received any benefits for this work.

References

1. Andriacchi TP, Dyrby CO, Johnson TS (2003) The use of functional analysis in evaluating knee kinematics. *Clin Orthop Relat Res* 410:44–53
2. Bellemans J, Banks S, Victor J, Vandenuecker H, Moemans A (2002) Fluoroscopic analysis of the kinematics of deep flexion in total knee arthroplasty. Influence of posterior condylar offset. *J Bone Jt Surg Br* 84:50–53
3. Chandran N, Amirouche F, Gonzalez MH, Hilton KM, Barmada R, Goldstein W (2008) Optimisation of the posterior stabilised tibial post for greater femoral rollback after total knee arthroplasty—a finite element analysis. *Int Orthop* [Epub ahead of print]

4. Coughlin KM, Incavo SJ, Doohen RR, Gamada K, Banks S, Beynnon BD (2007) Kneeling kinematics after total knee arthroplasty: anterior-posterior contact position of a standard and a high-flex tibial insert design. *J Arthroplast* 22:160–165
5. Delport HP, Banks SA, De Schepper J, Bellemans J (2006) A kinematic comparison of fixed- and mobile-bearing knee replacements. *J Bone Jt Surg Br* 88:1016–1021
6. Dennis DA, Komistek RD, Scuderi GR, Zingde S (2007) Factors affecting flexion after total knee arthroplasty. *Clin Orthop Relat Res* 464:53–60
7. Dennis DA, Komistek RD, Walker SA, Cheal EJ, Stiehl JB (2001) Femoral condylar lift-off in vivo in total knee arthroplasty. *J Bone Jt Surg Br* 83:33–39
8. Hamai S, Miura H, Higaki H, Matsuda S, Shimoto T, Sasaki K, Yoshizumi M, Okazaki K, Tsukamoto N, Iwamoto Y (2008) Kinematic analysis of kneeling in cruciate-retaining and posterior-stabilized total knee arthroplasties. *J Orthop Res* 26:435–442
9. Han HS, Kang SB, Yoon KS (2007) High incidence of loosening of the femoral component in legacy posterior stabilised-flex total knee replacement. *J Bone Jt Surg Br* 89:1457–1461
10. Hanson GR, Park SE, Suggs JF, Moynihan AL, Nha KW, Freiberg AA, Li G (2007) In vivo kneeling biomechanics after posterior stabilized total knee arthroplasty. *J Orthop Sci* 12:476–483
11. Hanson GR, Suggs JF, Freiberg AA, Durbhakula S, Li G (2006) Investigation of in vivo 6DOF total knee arthroplasty kinematics using a dual orthogonal fluoroscopic system. *J Orthop Res* 24:974–981
12. Hemmerich A, Brown H, Smith S, Marthandam SS, Wyss UP (2006) Hip, knee, and ankle kinematics of high range of motion activities of daily living. *J Orthop Res* 24:770–781
13. Jennings LM, Bell CJ, Ingham E, Komistek RD, Stone MH, Fisher J (2007) The influence of femoral condylar lift-off on the wear of artificial knee joints. *Proc Inst Mech Eng [H]* 221:305–314
14. Kim TH, Lee DH, Bin SI (2008) The NexGen LPS-flex to the knee prosthesis at a minimum of three years. *J Bone Jt Surg Br* 90:1304–1310
15. Lee SY, Matsui N, Kurosaka M, Komistek RD, Mahfouz M, Dennis DA et al (2005) A posterior-stabilized total knee arthroplasty shows condylar lift-off during deep knee bends. *Clin Orthop Relat Res* 435:181–184
16. Li G, Most E, Otterberg E, Sabbag K, Zayontz S, Johnson T et al (2002) Biomechanics of posterior-substituting total knee arthroplasty: an in vitro study. *Clin Orthop Relat Res* 404:214–225
17. Li G, Most E, Sultan PG, Schule S, Zayontz S, Park SE, Rubash HE (2004) Knee kinematics with a high-flexion posterior stabilized total knee prosthesis: an in vitro robotic experimental investigation. *J Bone Jt Surg Am* 86:1721–1729
18. Li G, Papannagari R, Li M, Bingham J, Nha KW, Allred D et al (2007) Effect of posterior cruciate ligament deficiency on in vivo translation and rotation of the knee during weightbearing flexion. *Am J Sports Med* 36:474–479
19. Li G, Suggs J, Hanson G, Durbhakula S, Johnson T, Freiberg A (2006) Three-dimensional tibiofemoral articular contact kinematics of a cruciate-retaining total knee arthroplasty. *J Bone Jt Surg Am* 88:395–402
20. Mulholland SJ, Wyss UP (2001) Activities of daily living in non-Western cultures: range of motion requirements for hip and knee joint implants. *Int J Rehabil Res* 24:191–198
21. Ng FY, Wong HL, Yau WP, Chiu KY, Tang WM (2008) Comparison of range of motion after standard and high-flexion posterior stabilised total knee replacement. *Int Orthop* 32:795–798
22. Park KK, Shin KS, Chang CB, Kim SJ, Kim TK (2007) Functional disabilities and issues of concern in female Asian patients before TKA. *Clin Orthop Relat Res* 461:143–152
23. Scuderi GR, Komistek RD, Dennis DA, Insall JN (2003) The impact of femoral component rotational alignment on condylar lift-off. *Clin Orthop Relat Res* 410:148–154
24. Suggs JF (2007) Investigation of in-vivo total knee arthroplasty biomechanics using a dual fluoroscopic imaging system. Dissertation, Massachusetts Institute of Technology, Cambridge, MA
25. Suggs JF, Hanson GR, Park SE, Moynihan AL, Li G (2008) Patient function after a posterior stabilizing total knee arthroplasty: cam-post engagement and knee kinematics. *Knee Surg Sports Traumatol Arthrosc* 16:290–296