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In vivo weight-bearing kinematics with medial rotation knee arthroplasty

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ABSTRACT

Knee arthroplasties are designed to accommodate flexion, axial rotation and anteroposterior (AP) translation. Axial rotation during extension varies, with some rotating platform devices allowing unrestricted rotation while some conforming fixed-bearing designs almost none. The purpose of this study was to examine *in vivo* kinematics of a fixed-bearing medial rotation-type arthroplasty (MRK) during weight-bearing activities. Fifteen knees with a medial pivot TKA design were studied during step and pivot activities using lateral fluoroscopy and model-image registration. Average knee kinematics during the step activity showed little AP translation or rotation from 0°–100° flexion. During the pivot activity, the mean tibial internal rotation in individual knees was 7° (3°–19°). Mean condylar translations for individual knees were 3 mm medially and 5 mm laterally. The medial pivot prosthesis design provides anteroposterior stability during demanding activities, and exhibits a medial pivot motion pattern when subjected to twisting.

1. Introduction

Total knee arthroplasty (TKA) is an extremely successful procedure with a survivorship of around 90–95% at 15–20 years[1,2]. The aims of knee arthroplasty are to reduce pain, provide stability and restore knee function. Various surgeons and designers have advocated the retention of the posterior cruciate ligament (PCL) to improve the mechanical efficiency of the knee musculature and stair-climbing function [3] and maintenance of proprioception after TKA. Even though the PCL-retaining TKAs have shown excellent clinical and functional outcomes, numerous radiographic and fluoroscopic studies have shown anterior femoral translation with flexion and abnormal kinematics *in vivo* during various activities [4–8]. PCL-substituting knee arthroplasties have shown more predictable kinematics than PCL-retaining knees [6,9–11]. However, there is still concern regarding wear occurring on the cam-post mechanism in fixed-bearing prostheses [12–14], sparking renewed interest in mobile-bearing designs. In a mobile-bearing prosthesis, the insert is able to axially rotate on the metal tibial component and allow joint torques to be transferred to the soft tissues, which is hypothesised to reduce loosening stress at the bone-implant interface [15].

Reports from *in vivo* fluoroscopic studies comparing axial rotation between fixed-bearing and mobile-bearing prosthesis are inconsistent. Ranawat et al. [16] found a mean tibial internal rotation of 7.3° for a mobile-bearing TKA, and 4.1° for fixed-bearing TKA during a deep knee bend. However Dennis et al. [17] studied axial rotations during deep knee bend, in 76 PCL-sacrificed mobile-bearing TKA and 212 PS-fixed-bearing TKA and found no difference (5.5° of internal rotation and 2.1° of external rotation). However, all these studies focused only on straight ahead squatting type of tasks, and may therefore underestimate possible differences in freedom of axial rotation. In the kinematic evaluation of TKA, especially when axial rotation is investigated, it may be necessary specifically to study turning tasks.

The importance of turning steps during activities of daily living was emphasized in a video analysis by Glaister et al. [18]. For instance, during walking through a cafeteria, up to 50% of steps taken were turning steps. Zurcher et al. [19] investigated the influence of turning on 15 normal axial knee rotations and found the combined axial rotation range for crossover and sidestep turns was 20.9° versus 13.5° for the standard chair rise ($p<0.0001$). They concluded that this unique set of tasks may be useful in the studies that aim to compare freedom of axial rotation in different designs of TKA. To date, there has been no kinematic evaluation of TKA designs during turning tasks to find possible differences between designs with respect to axial rotation.

Among the design alternatives to traditional PCL-retaining and PCL-substituting types are devices which incorporate a highly conforming medial tibiofemoral articulation as a surrogate stabilizer for the natural cruciates and menisci. These so-called medial rotation devices provide intrinsic anteroposterior stability through the conforming medial articulation and couple tibial rotation to anteroposterior translation of the lateral femoral condyle. The first device of this type was a derivative of the Freeman–Samuelson design. Advocates suggest the combination of large contact areas and replication of major features of natural knee motion should benefit device longevity and patient satisfaction. However, very few studies have been reported on the kinematics of

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the medial pivot knee [20,21]. Saari et al. [20] described the kinematics during active weight-bearing extension from 45° to 15° while Schmidt et al. [21] examined the knee during gait initiation.

The aim of this study was to measure the *in vivo* kinematics of a semi-constrained medial rotation knee (MRK) arthroplasty during weight-bearing stepping and pivoting (crossover) activities. The authors hypothesised that, because of the medial ball and socket design, these knees will show a medial pivot kinematic pattern with posterior translation of the lateral femoral condyle coupled to tibial internal rotation with knee flexion. Also, during the pivoting manoeuvre, even with the increase in the torque forces around the knee, we expected that the medial compartment would remain congruent throughout the task and an increase in axial rotation would be seen.

2. Material and methods

Thirteen patients (15 TKAs, four males and nine females) gave written consent to participate in this ethics committee approved study. The patients were studied using lateral fluoroscopic imaging during a step-up activity. Ten patients (11 TKA's, three males and seven females) were sufficiently athletic also to complete a weight-bearing pivot activity.

A medial pivot prosthesis (Medial Rotation Knee (MRK), Finsbury Orthopaedics, Surrey, UK) was used in all knees. The MRK has a ball and socket articulation on the medial side which provides complete congruency from full extension to 100° flexion. Beyond 100°, flexion is not limited but the posterior extremity of the femoral condyle passes anterior to the posterior extremity of the tibial surface. Contact area is reduced, but coronal conformity is maintained. The lateral surface is formed as a cone, centred on the medial sphere. This results in full congruency when the femur is in full extension. The MRK is a posteriorly stabilised knee with posterior stability provided by the position of the raised anterior lip on the medial tibial articular surface which conforms with the spherical femoral surface to a depth of 11 mm (Fig. 1).

Patient preselection was performed in the outpatient clinic. Patients were selected who had pre-operative diagnosis of primary osteoarthritis, post-operative collateral ligament stability, Oxford knee score less than 25, an International Knee Society score greater than 85, a range of motion in excess of 90° and an ability to kneel comfortably on their replaced knee (Table 1). The study was approved by the Research Ethics committee at our institution and informed consent was obtained from all patients.

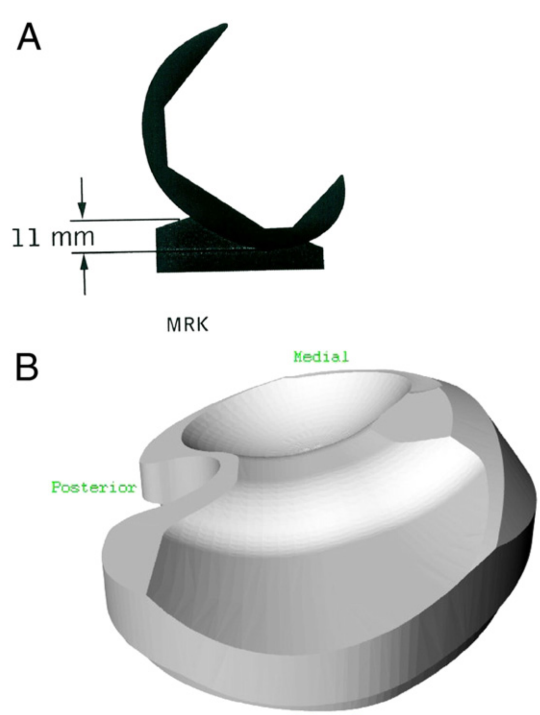

Fig. 1. A: Sagittal section of the medial side of the medial rotation knee prosthesis. B: Lateral view of the medial knee rotation prosthesis showing the medial ball in socket joint and lateral flatter surface.

Table 1
Demographic details.

	Mean	Standard deviation	Range
Age (years)	75	7	61–86
BMI	32	5	20–38
Time of follow-up (mo)	17	4	13–27
Oxford knee score	17	3	12–23
Knee score	95	3	86–98
Functional score	99	2	94–100
Post-op coronal alignment	7° valgus	2°	4°–11°
Tibial component slope	2°	3°	−4°– 4°

The patients were operated by two surgeons (REF and GTR). All patients had knee replacement through a medial parapatellar exposure. All components were cemented. The PCL was divided in all cases. The patella was resurfaced in ten knees. Intramedullary alignment was used for the femur and the extramedullary for the tibia. Sizing of the distal femur was performed with anterior referencing instrumentation in order to restore both the joint line and the flexion gap balanced as accurately as possible. The tibial component size and position was determined with the trial components allowing the femur to determine its best position. All the patients had identical post-operative care and rehabilitative protocol.

3. Outcome

Outcome parameters other than those based on fluoroscopy included evaluation of the Oxford knee score [22] and International Knee Society score [23]. All scores were obtained, and measurements made and recorded by a clinical research fellow (Table 1).

4. Radiological analysis

An independent orthopaedic surgeon measured component alignment and identified radiolucent lines using the Knee Society radiological evaluation system [23]. No significant radiolucencies were observed. Weight-bearing anteroposterior and lateral radiographs were acquired during routine clinic visits and examined for limb alignment and position of the components. Sagittal alignment was measured as the angle between the undersurface of the tibial tray and a line perpendicular to the posterior tibial shaft (Table 1).

5. Fluoroscopy

Knee motions were recorded using fluoroscopy as subjects did single-leg stepping up and down on a stair. Subjects began by placing their ipsilateral foot on a 25-cm riser. They were instructed to rise to full knee extension on the step, not swinging through with the opposite leg, then reverse direction to the starting position. An investigator offered to hold the patient's hands or forearms for safety, but did not lift the subjects. For the pivot activity, patients started with their contralateral leg and body rotated away from the stance leg (tibial external rotation), and then pivoted on their implanted stance leg to induce maximum tibial internal rotation and then reverse the direction to the starting position. An investigator again offered to hold the patients' hands or forearms as a safety measure.

Images were recorded at 10 frames/s using a mobile C-arm system (Philips BV Libra) operated in pulse mode. The video images were recorded digitally in DICOM format.

The three-dimensional position and orientation of the proximal and distal arthroplasty components were determined using a toolbox of model-based shape-matching techniques, including previously reported techniques [4], manual matching, and automated matching using nonlinear least-squares (modified Levenberg–Marquardt) techniques. Five hundred and eighty eight fluoroscopic images, an average of 39 images per knee (range 21–49), were analysed. The optical geometry of the fluoroscopy system (principal distance, principal point) was determined from the images of a calibration target [4]. 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. The results of this shape-matching process have standard errors of approximately 0.5° to 1.0° for rotations and 0.5 mm to 1.0 mm for translations in the sagittal plane [4].

Joint kinematics were determined from the three-dimensional pose of each TKA component using Cardan/Euler angles [24]. The anterior/posterior locations of the contact points were determined by transforming the joint pose into a reference system parallel to the transverse plane of the tibial baseplate and finding the lowest point on each femoral condyle. The mean centres of axial rotation were determined from lines connecting the medial and lateral condyle locations during the stair and pivot activity.

Medial and lateral sides were analysed separately. The reference line for translations of the contact points was centred on the spherical recess in the tibial insert, which was 18 mm from the posterior edge of the insert in all sizes. Data was stored and analysed in Microsoft Excel. The standard deviation has been calculated using multiple measurements per patient; it does not represent the spread of this variable in a population.

6. Results

6.1. Stair/steps activity

The medial and lateral femoral condylar translations were similar in both the flexion and the extension phase of the step-up activity. From hyperextension to 20° of flexion, the medial tibiofemoral contact point translated anteriorly by an average of 1.0 mm, with less than 1 mm additional translation through 100° of flexion (Table 2, Fig. 2). Ensemble average lateral condyle translations were less than 1 mm from hyperextension to 100° flexion. All knees exhibited condylar positions aligned with the deepest points on the tibial insert.

From extension to 100° of flexion, the average for all knees showed average axial rotations of 1° or less. The average range of rotation for individual knees was 5° (range 1° to 8°). The maximum tibial internal rotation seen in any patient during step-up was 6.3° at 75° of flexion in the transition from relaxed stance to active step ascent.

Tibial valgus averaged 2° of varus in 10° hyperextension (1 knee), but averaged less than 1° from 0° to 100° flexion (Table 2). Four knees showed a coronal rotation of greater than 3° in relaxed stance prior to active step ascent. All knees measured less than 3° of varus/valgus deviation during the active step ascent.

6.2. Pivot activity

The patients started the pivot activity with the knee slightly flexed with tibial external rotation, and then extended their knees as they pivoted to tibial internal rotation (Fig. 3). At 9° of external rotation the mean position of the medial and the lateral condyles were -3 ± 1 mm and $+4\pm2$ mm respectively. With tibial internal rotation, the medial condyle moved to the centre of the tibial sulcus, varying not more than 2 mm in the anteroposterior direction, while the lateral condyle moved posteriorly by an average of 10 mm to lie at -6 ± 0.2 mm at 9° internal rotation. The mean tibial internal rotation in individual knees was 7° (3°–19°). Mean condylar translations for individual knees were 3 mm medially and 5 mm laterally. At 30° flexion the average tibial rotation was $5°\pm1°$ while the mean tibial rotation at hyperextension was $-2°\pm1°$. At the extremes of the axial rotation, knees showed a varus rotation coupled to condylar translation on the curved tibial articular surfaces (Table 3).

Table 2
Knee kinematics for step activity.

Flexion (deg)	Tibial external rotation (deg)	Medial AP position (mm)	Lateral AP position (mm)	Valgus (deg)	No. of knees	No. of observations
−10	0.14	−1.3	−0.7	−2.28	1	11
0	−0.09	0	−0.2	−0.47	7	45
10	−0.25	0.1	−0.2	−0.78	11	63
20	−0.28	−0.3	−0.4	−0.8	14	41
30	0.84	−0.2	0.2	−0.48	15	41
40	0.51	−0.3	0	−0.71	15	41
50	0.05	0.1	0.1	−0.8	15	30
60	0.14	0.1	0.2	−0.71	15	33
70	−1.11	0.5	−0.2	−0.29	15	38
80	0.11	−0.1	−0.3	−0.16	13	68
90	0.7	−0.3	0.2	0.03	9	72
100	−1.3	0.6	−0.7	0.01	3	10

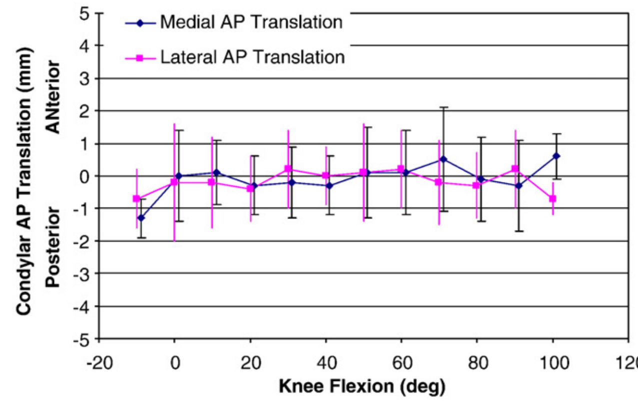

Fig. 2. Anteroposterior translations of the medial and lateral condyles averaged less than 1 mm across the range of flexion during the step-up activity.

7. Discussion

Various factors including implant design, surgical procedure and different weight-bearing activities affect knee kinematics after TKA. We measured knee motions in patients with medial pivot knee prostheses during step and pivot activities. The step activity was chosen as a physically demanding, large range of motion activity for which there is an abundance of published results for comparison. The pivot exercise was chosen to exert a large torque on the TKA, permitting observation of induced condylar translations in the semi-constrained medial pivot design. The MRK has been in use since 1994 and a few studies have reported its kinematics [21,25]. However this is the first study to report the kinematics of MRK during the pivot activity. The main finding in this study is that the medial articular surface is antero-posteriorly stable in both the non-weight-bearing and weight-bearing phases. The lateral articular surface also shows negligible translation during the stair activity.

This study has several limitations. First, there is neither a natural or prosthetic knee control group for kinematic comparisons, thus comparison only can be made to similar previously published studies. Second, the fluoroscopic equipment recorded relatively low resolution

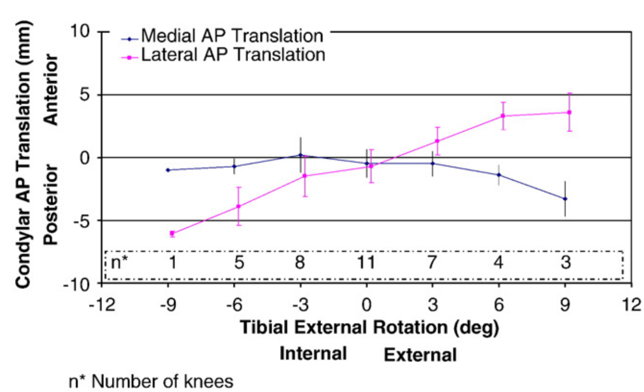

Fig. 3. Anteroposterior translations of the medial and lateral condyles during the pivot activity. The AP translation averaged less than 2 mm for the medial side while the lateral side shows a linear relationship with axial rotation.

Table 3
Kinematics of the knee during pivot activity.

External tibial rotation (degrees)	Flexion (degrees)	Medial AP translation (mm)	Lateral AP translation (mm)	Abduction (degrees)	No. of knees	No. of observations
9	15.39	−3.3	3.6	−1.33	3	5
6	13.05	−1.4	3.3	−0.42	4	16
3	13.51	−0.5	1.3	−0.92	7	40
0	5.46	−0.5	−0.7	−0.56	11	104
−3	3.7	0.2	−1.5	−0.6	8	40
−6	5.31	−0.7	−3.9	−1.24	5	13
−9	−2.6	−0.1	−6.1	−2.76	1	2

images and had limited pulse capabilities. These limitations required activities to be performed at moderate speeds to avoid motion blur in the images. Third, we recruited well performing patients in order most clearly to observe the influence of the prosthesis design. This subject selection results in data which are not necessarily representative of the entire clinical population receiving this design. Finally, movements during the step and pivot activities were confined to the arc of motion in which the prosthesis is fully congruent, thus an assessment of the entire functional range of the prosthesis is not provided.

There have been very few reports on the kinematics of a medial pivot knee [20,21]. Saari et al. [20] studied the kinematics of eight medial pivot knees with full to partial PCL retention ascending an 8-cm step using radiostereometric analysis (RSA). They observed a mean external rotation of 2.9° from 15° to 45° of flexion and a mean valgus angulation (based on bone reference systems) of 5.2° at 45° of flexion. Compared to the previous studies, we observed similar condylar translations but somewhat different rotations [20,21]. We observed an internal rotation of 1° and no abduction with flexion. This is contrary to the observations seen by Saari et al. [20], and may be explained either by the fact that different measurement methods and bone/implant coordinate systems were used or due to the absence of the PCL in knees in the present study. When maintained, the PCL may act as an eccentric tether or tension band that constrains the axial rotations of the tibia with respect to the femur [5].

Stair activity, which is quite mechanically demanding, has been used in multiple studies to compare or differentiate between PCL-retaining (PCL-R), PCL-sacrificing (PCL-S) and mobile-bearing TKAs [5,9,26–30]. Banks et al. [5] studied the kinematics of three groups of knee arthroplasty during a step-up activity. Knees with fully retained PCL showed anterior lateral translation while knees with recessed PCL showed posterior lateral translation from flexion to extension. Knees with greater sagittal conformity and post/cam substitution of the sacrificed PCL exhibited 1 mm condylar translation throughout the activity. In the current study, the kinematics of the medial pivot knee (MRK) were similar to the more conforming posteriorly stabilized design during the step activity. On average, the two femoral condyles did not show any AP translations — neither paradoxical nor physiological. Also the MRK knees did not produce any rotation during this activity. This may be because the stair activity does not produce enough rotational torque to cause axial rotation at the articular surface.

Turning steps are present during all kinds of activities, and from Glaister et al. [18], we know they make up a considerable portion of steps taken during daily walking. Zurcher et al. [19] have shown that crossover and sidestep activities induce a large amount of axial rotation in the knee (20.9°). Noble et al. [31] reported many TKA patients had difficulty performing turning/cutting activities, despite the fact that patients performed the activities with the same frequency as non-TKA controls. This study's pivot activity was intended to produce enough torque to induce knee rotation. We have demonstrated that a pivot activity significantly increases tibial axial rotation in the medial pivot knee replacement. During the pivot activity all knees rotated internally with a mean tibial internal rotation 7° around the medial femoral condyle and the lateral femoral condyle moved posteriorly by 10 mm. This is consistent with the design of the MRK polyethylene insert which has a flat surface of around 7 mm (depending on the size of the insert) on the lateral articular surface.

As the long term survivorship of TKA has increased, the focus of many surgeons and engineers has changed to improving the functional performance of TKA. There have been various studies on the functional performance of TKA during chair-rise and stair-climbing activities which have demonstrated more normal joint power and kinematics in knees with intrinsically stable prostheses [9,32–34]. Andriacchi et al. [32] studied with gait analysis a variety of TKA designs during stair-climbing and concluded that knees with bi-cruciate retaining TKA exhibited the most normal gait patterns. Draganich et al. [33] showed that knees with an early engaging PCL-S TKA design had better quadriceps efficiency than knees with a late engaging PCL-S TKA. This may be because of the intrinsic AP stability provided by the early engaging post/cam mechanism. Medial pivot TKA designs also provide intrinsic joint stability through their conforming tibiofemoral articulation and might reasonably be expected to exhibit consistent kinematics and good quadriceps efficiency and patient functional strength. Pritchett [35] reported that patients with bilateral TKA of two types overwhelmingly preferred their knee with either a bi-cruciate retaining or pivoting a design over a standard PCL-R or PCL-S design.

In four knees during the pivot activity we observed varus deviation of approximately 3° at the extremes of rotation. This coronal rotation is consistent with one or both condyles translating up the slope of the deepened tibial sulcus with forced axial rotation. Similar movements were observed by Saari et al. [20]. The lateral condyle translated posteriorly (and up) with forced tibial internal rotation, while both condyles appear to screw upward (more laterally) on the tibial surface with forced tibial external rotation. These coupled translations place the condyles on less conforming regions of the tibial articular surface, where presumably some damage could accumulate if forced axial rotation were a feature of routine activity.

In summary, 15 knees with a medial pivot TKA design were studied during step and pivot activities. Average knee kinematics during the step activity showed little AP translation or rotation from 0°–100° flexion. A medial pivot motion pattern was observed during weight-bearing pivoting. Average axial rotation was 7°, less rotation than is observed in normal knees.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.knee.2009.06.009.

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