Accurate measurement of three-dimensional knee replacement kinematics using single-plane fluoroscopy: In vivo study of the GMK Sphere Total Knee Arthroplasty

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Abstract

The GMK Sphere is a new total knee arthroplasty (TKA) designed to allow more natural internal and external tibial rotation while maintaining anterior/posterior stability during a range of activities. In this study, fluoroscopic data was collected from 15 patients with 16 implants and knee kinematics were measured using model-image registration. At average maximum flexion of approximately 120˚ in lunging and kneeling, the corresponding tibial rotation averaged 8˚. In a cyclic step up/step down activity ranging 10-70˚ of flexion, tibial rotation averaged 5˚. Over that same range, the anterior/posterior translations averaged -1mm and -4mm for the medial and lateral condyles, respectively. This implant design follows a similar kinematic pattern to a healthy knee, but tibial rotations and condylar translations were smaller in magnitude. The GMK Sphere appears to function in vivo in a manner consistent with the goals of the design, and allows for individual variations across a wide range of activities.

Introduction

Total knee arthroplasty (TKA) is a common procedure, with 719,000 surgeries performed in the United States in 2010 [1]. There are several different designs of these orthopedic prosthetics, notably posterior cruciate ligament (PCL) retaining and PCL substituting cam-and-post designs. More recent TKA implants have focused on mimicking the kinematics of healthy knees, which exhibit a medial pivoting motion relative to the tibia in flexion [2]. Knee prostheses with this emphasis on medial rotation have been shown to have similar kinematic patterns to healthy knees, and may help reduce the wear on the polyethylene inserts compared to cam-and-post designs [3,4].

The GMK Sphere TKA is a new prosthesis based on the clinically successful medial rotation knee (MRK) prosthesis. Fluoroscopic kinematic studies carried out previously on several medially constrained knee designs show exceptionally stable knee function and good functional attributes, but very small ranges of tibial internal/external rotation compared to the natural healthy knee [3,5]. This new design aims to improve patient range of motion by having a sagittally unconstrained lateral tibiofemoral articulation, which will allow more natural tibial internal and external rotation. This greater amount of internal/external rotation is believed to provide a higher level of individuality for the patient, as it can accommodate his or her specific implant alignment and loads during various activities.

Through the use of fluoroscopic images, this study aims to examine the kinematics of the TKA throughout the range of motion of the knee, with the express purpose of comparing this prosthesis to previous designs. Specifically, this study seeks to determine if knees with the GMK Sphere TKA provide sufficient rotational laxity to allow tibiofemoral rotations comparable to (but not larger than) rotations measured in natural knees, and whether these knees have a stable anterior-posterior articulation during weight-bearing flexion activities.

Methods

An in vivo kinematic analysis of kneeling, lunging, step-up, and rotation activities after TKA was performed on 16 knees in 15 different patients at 6-12 months post-surgery (**Table 1**). A medial-pivot, PCL-sacrificing prosthesis (GMK Sphere) was used in each patient. The patients were operated on by 3 surgeons (Richard Field, Gareth Scott, John Skinner), and all implants were cemented. Extramedullary alignment was used for the tibial resection, and intramedullary alignment was used for femur surface preparation.

Table 1: Patient Demographics			
	Mean	Standard Deviation	Range
Age (years)	65		53-75
BMI	30	3	
Oxford Knee Score	40	3	
Pre-op Knee Score	19	7	
Post-surgery Supine Active ROM	108˚	8˚	

The inclusion criteria for this study allowed for patients who were willing to provide informed written consent and participation. Patients who could not provide informed consent were not considered. Only patients aged between 50 and 85 years at the time of surgery, with excellent clinical and functional results of TKR as measured by Knee Society Score (>89) and Oxford Knee Score (>26), and with well-aligned implant components, having passive range of motion from 0^o-5^o to $>90^o$ were recruited. The exclusion criteria exempted patients with cognitive impairment, learning disabilities or alcohol or drugs dependency. We did not include pregnant women, patients with a body mass index (BMI) exceeding 35 kg/m^2, or those being treated for a local or systemic infection. Patients in which prospects for a recovery to independent mobility were compromised by coexistent medical problems or significant concurrent joint involvement were similarly excluded. The principal investigator or a suitably trained member of his team took consent before enrollment in the study.

Fluoroscopy

All patients were invited to the Elective Orthopaedic Centre in Epsom, UK, for fluoroscopic studies. The device used to capture the images was a C-arm fluoroscopy system (Philips MD4), operated in a pulse mode, and the images were recorded digitally in a DICOM format. The fluoroscopic C-arm was positioned to obtain a sagittal projection of the knee in motion. Images were acquired at 30 frames per second with approximate imaging parameters of 70 kVp (peak accelerating voltage) and 2 mA (electrical current). Total fluoroscopy exposure for all activities was approximately 30-40 seconds.

The patients were fluoroscopically evaluated in five activities: 1) weight-bearing lunge on a 22 cm step from approximately 90˚ of flexion to full comfortable flexion; 2) weight-bearing kneeling from 90˚ to full comfortable flexion; 3) seated internal rotation with knee at approximately 90˚ flexion; 4) seated external rotation with knee at approximately 90˚ flexion; and 5) stepping up and down on a 22 cm step without swing-through of the contralateral leg.

Three-dimensional orientation and position of the femoral and tibial components were determined using model-image registration, both manually and with automated non-linear least squares optimization [3]. The geometry of the fluoroscopy system was accounted for by a series of calibration images, and the implant model was projected onto the geometry-corrected image. The three-dimensional pose of the implant projection was then adjusted to match the silhouette of the patient's knee components for each frame of each activity. Joint rotations were expressed using an ordered sequence of flexion – abduction – external rotation parameters. Condylar anterior-posterior translations were determined by the lowest point on each femoral condyle relative to the sulcus location on the tibial surface.

Results

In the weight-bearing lunging activity, the average flexion angle was 120˚ ± 12˚ and tibial internal rotation averaged 8˚ ± 6˚. For kneeling, the average flexion angle achieved was 124˚ ± 10˚ with 8˚ ± 6˚ of tibial rotation. The internal and external rotations (shown in **Figure 1**) resulted in an average tibial rotation range of 16˚, with a bias toward internal rotation. The step up/step down activity was examined in the range of 10˚ to 70˚ of flexion, and showed an average tibial rotation of 5˚. As shown in **Figure 2**, however, rotations in each knee were highly individual.

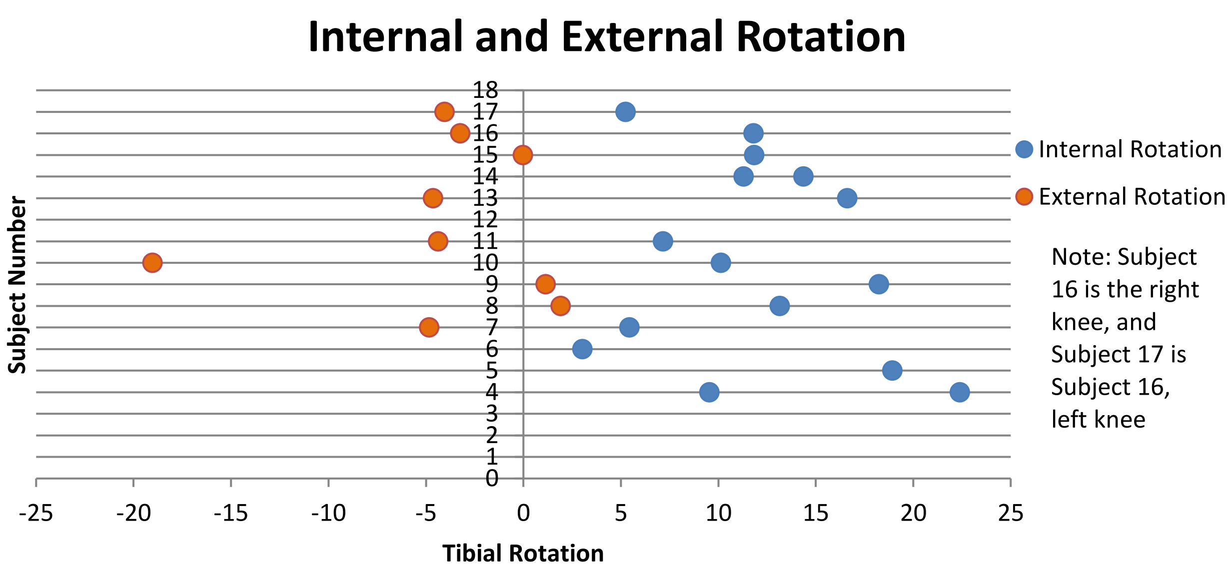

Figure 1: Tibal rotation in internal and external rotation trials.

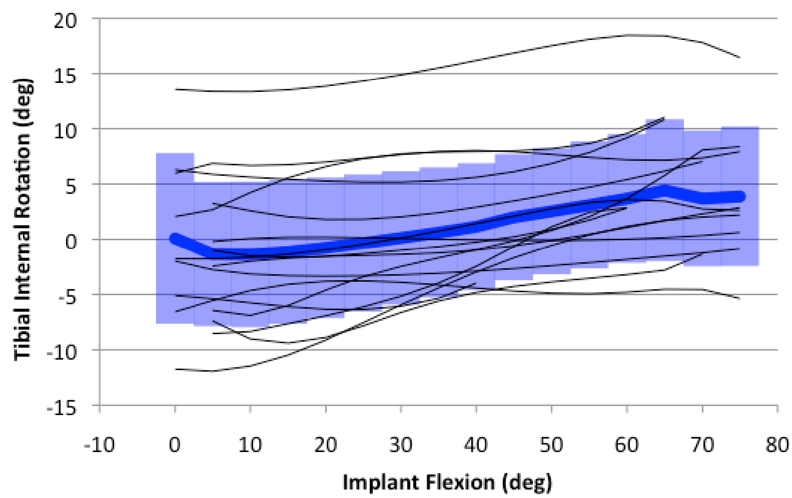

Figure 2: Tibial rotation as a function of implant flexion during step up/step down activity. Each black line represents an individual patient, while the blue line shows the average and the blue shading shows +/- one standard deviation. This graph shows the wide variability in rotation between patients.

The anterior/posterior translation of each femoral condyle was also examined for each activity. In lunging, an average flexion of 120˚ resulted in a medial translation of -2 ± 3mm and lateral translation of -8 ± 4mm. A projection of all of the lowest condylar points in lunging is shown in **Figure 3**. For the kneeling activity (average flexion angle of 124˚) the medial translation was -2 ± 4mm and the lateral translation was -9 ± 4mm. **Figure 4** shows the projection of all lowest points for this activity. Through the range of motion of the step up/step down activity, the average medial translation (**Figure 5**) was -1 mm and the average lateral translation (**Figure 6**) was -4mm. As with tibial rotation, translation in the lateral condyle was highly individual, and was inversely correlated with degree of tibial rotation.

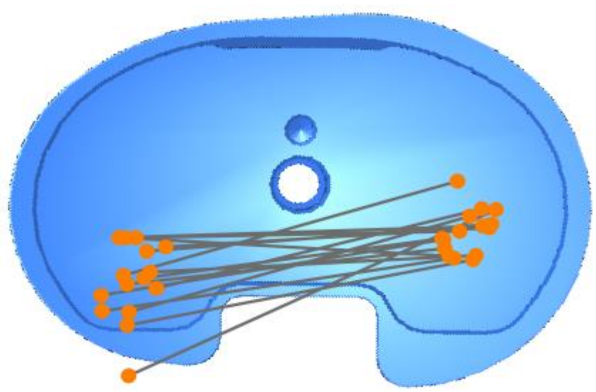

Figure 3: Projection of lowest condylar points during lunge activity.

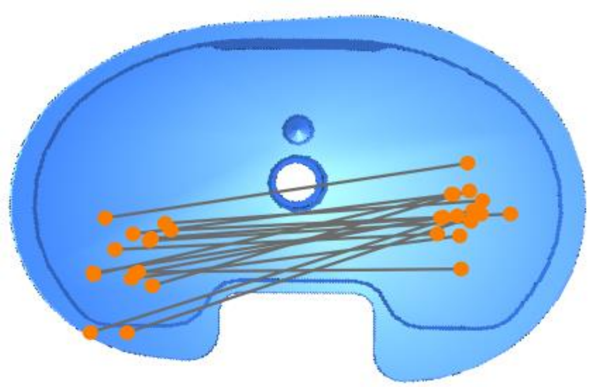

Figure 4: Projection of lowest condylar points during kneeling activity.

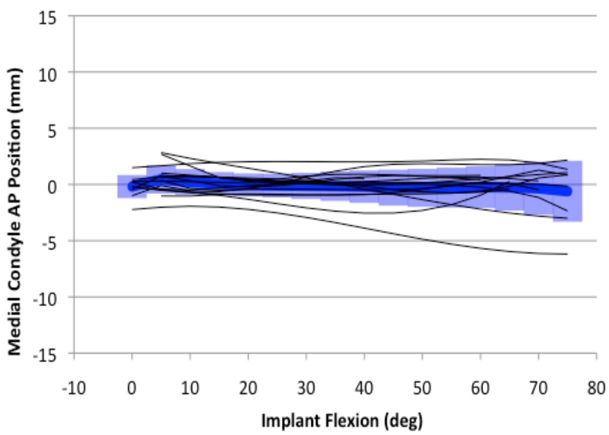

Figure 5: Medial condylar translation as a function of implant flexion during step up/step down activity.

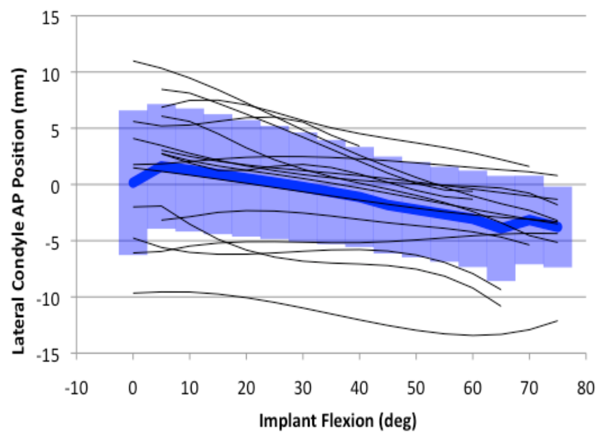

Figure 6: Lateral condylar translation as a function of implant flexion during step up/step down activity.

Discussion

The purpose of this study was to examine whether the new GMK Sphere TKA allows for tibial rotations and anterior-posterior translations that correspond to the kinematics of a healthy knee. As patients requiring TKA surgeries become younger and more active, they desire an implant that allows them to enjoy their favorite activities without hindering performance. The GMK Sphere hopes to provide stability and flexibility in a wide range of activities, in order to better fit the needs of every individual. Our data show the GMK Sphere TKA moves as a medial-pivot articulation for the activities observed.

Healthy and osteoarthritic knee kinematics have been studied previously in the same activities performed during this study [6,7]. For young, healthy knees, 120˚ of flexion in the kneeling activity resulted in 13˚ of tibial rotation [6]. In arthritic knees, the same activity produced 14˚ of tibial rotation [7]. In the current study, the kneeling and lunging activities (with flexion angles of 120˚ and 124˚, respectively) both resulted in an average of 8˚ of tibial rotation. These data are comparable to other TKA designs, with a posterior stabilized cam-and-post corresponding with 6˚ of tibial rotation at 120˚ flexion during lunging, and the medial rotation knee allowing 3-4˚ of rotation in lunging and kneeling at 120˚ [8,4]. During the step up/down activity, the healthy knees showed an average of 9˚ of tibial internal rotation from 10˚-70˚ flexion, and osteoarthritic knees showed 7.5˚ of tibial internal rotation over the same flexion range [6,7]. Knees with the GMK Sphere averaged 5˚ of tibial internal rotation over 10˚-70˚ flexion, while the posterior-stabilized and MRK designs averaged 6˚ and 1˚, respectively [8,4]. Although the GMK Sphere does not achieve physiological rotation values, it is similar to the posterior stabilized design and shows improvement over the medially-rotating knee.

The translations of the medial and lateral condyles of the femur are also important to normal knee kinematics. For the step up/step down activity (range of motion 10˚-70˚), healthy knees showed average medial translation of -5mm (i.e. 5mm posterior) and lateral translation of -6mm [6]. Arthritic knees showed similar results, with average translations of -3mm medially and -6mm laterally [7]. For the GMK Sphere, the medial translation averaged -1mm and the lateral translation averaged -4mm. These results indicate posterior translation of both condyles, which is consistent with the kinematics of healthy knees. The posterior-stabilized design actually resulted in anterior translation of the medial condyle, with an average value of +3mm, and no translation of the lateral condyle [9]. The MRK TKA averaged 0mm of translation in both condyles, acting as a hinge over the flexion range of interest [4]. Neither of these previous implant designs shows kinematic patterns consistent with those of a healthy knee, so the GMK Sphere may be considered closer to physiologic than either the posterior-stabilized or MRK TKAs.

Conclusions

Knees with the GMK Sphere TKA exhibit tibial rotations that are smaller than those of healthy knees over a range of activities. This implant does allow for more rotation than previous medially-stabilized designs, and values for rotation are comparable to those found in posterior-stabilized designs. The GMK Sphere also results in similar translation patterns to those of healthy knees, even though the magnitude of translation for each condyle is smaller. This design is also intrinsically stable in anterior/posterior motion, and does not exhibit the paradoxical anterior translation that is characteristic of many other TKA designs. Most importantly, the in vivo kinematics reflect knee function that is consistent with the goals of the design, allowing a wider range of motion for patients so they can enjoy more activities.

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Disclosure

This study was conducted under research contract between the University of Florida and Medacta International.

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