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Kinematics and early migration in single-radius mobile- and fixed-bearing total knee prostheses

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ABSTRACT

Background: The mobile-bearing variant of a single-radius design is assumed to provide more freedom of motion compared to the fixed-bearing variant because the insert does not restrict the natural movements of the femoral component. This would reduce the contact stresses and wear which in turn may have a positive effect on the fixation of the prosthesis to the bone and thereby decreases the risk for loosening. The aim of this study was to evaluate early migration of the tibial component and kinematics of a mobile-bearing and fixed-bearing total knee prosthesis of the same single-radius design.

Methods: Twenty Triathlon single-radius posterior-stabilized knee prostheses were implanted (9 mobile-bearing and 11 fixed-bearing). Fluoroscopy and roentgen stereophotogrammetric analysis (RSA) were performed 6 and 12 months post-operatively.

Findings: The 1 year post-operative RSA results showed considerable early migrations in 3 out of 9 mobile-bearing patients and 1 out of 11 fixed-bearing patients. The range of knee flexion was the same for the mobile-bearing and fixed-bearing group. The mobile insert was following the femoral component during motion.

Interpretation: Despite the mobile insert following the femoral component during motion, and therefore performing as intended, no kinematic advantages of the mobile-bearing total knee prosthesis were seen. The fixed-bearing knee performed as good as the mobile-bearing knee and maybe even slightly better based on less irregular kinematics and less early migrations.

1. Introduction

The conventional knee implant is designed with several axes of rotation, the so called multi-radius designs. In multi-radius designs the motion of the knee is guided by the shape of the articulating surfaces (Banks et al., 1997; Kessler et al., 2007; Pandit et al., 2005). During knee flexion, the contact area between the femoral component and the insert decreases which can lead to excessive stresses in the polyethylene (Blunn et al., 1997). Because of the change in radii of the femoral component, strain on the ligaments is not consistent during motion. This ligament instability tends to cause the femoral component to skid forward rather than roll back during flexion (paradoxical anterior motion). This may lead to impingement during deep flexion thereby limiting the range of motion. Alternatively, single-radius designs have been developed allowing the ligaments to guide the motion of the knee on the articulating surfaces. According to the design rationale of a single-radius design, centering the axis of rotation about the transepicondylar axis provides ligament isometry and a substantial contact area throughout the entire range of motion. This provides a more uniform motion, lower contact stresses on the insert, better mid-flexion stability and more efficient muscle activity (Blunn et al., 1997; Hollister et al., 1993; Kessler et al., 2007; Mahoney et al., 2002; Wang et al., 2005, 2006).

The mobile-bearing variant of this single-radius design is assumed to provide more freedom of motion compared to the fixed-bearing variant because the insert can move with respect to the tibial component and does not restrict the natural movements of the femoral component. This would reduce the contact stresses and polyethylene wear even further. Furthermore, the concept of the mobile-bearing implies uncoupling of the forces generated at the articulation from the bone–implant interface. This may have a positive effect on the fixation of the prosthesis to the bone and thereby decrease the risk for loosening (Garling et al., 2005b; Henricson et al., 2006; Huang et al., 2007).

The aim of this study was to evaluate and compare kinematics as well as early migration of the tibial component of a mobile-bearing and fixed-bearing total knee prosthesis of the same single-radius design.

2. Methods

The patients included in this fluoroscopic study were part of a larger prospective randomized roentgen stereophotogrammetric analysis

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(RSA) trial, studying the long-term fixation of the tibial component of the Triathlon total knee prosthesis (Stryker Orthopaedics, USA). All osteoarthritic and rheumatoid arthritic patients of our hospital undergoing primary total knee arthroplasty were included in the large RSA study, except those having a flexion or varus–valgus contracture of 15° or more. Using block randomization patients were allocated to the mobile-bearing or fixed-bearing group. The surgeons were informed about the type of implant just before surgery. Prospectively, the first 20 patients of the larger RSA study, who met the inclusion criteria for this fluoroscopic study, were included for this smaller study. Inclusion criteria were the expected ability of patients to perform a step-up and lunge motion 6 months post-operatively in a controlled manner without the use of bars and walk more than 1 km. All patients met the inclusion criteria at 6 months. Twenty knees, in 17 patients (11 female; 6 male) were included and evaluated using fluoroscopy while performing a step-up and lunge motion 6 (FU1) and 13 (FU2) months after total knee arthroplasty (Table 1). Three knees were randomly selected to receive a mobile-bearing knee, however, by decision of the surgeon they were implanted with a fixed-bearing knee. Analysis is performed according to ‘applied treatment’. Based on a previous fluoroscopy study, relative motions of 0.3° could be detected when ten patients were included in each group (Kaptein et al., 2003). All patients gave informed consent and the study was approved by the local medical ethics committee. Patients' reported functional ability (knee score and function score) were quantified 1 week before surgery and post-operatively at 6 and 13 months using the Knee Society Score (KSS) (Ewald, 1989). All surgeries were considered clinically successful; patients had no significant pain or measurable ligamentous instability.

The Triathlon total knee prosthesis is a single-radius posterior-stabilized knee prosthesis. The femoral component was the same for the mobile-bearing and fixed-bearing implant with a single-radius resulting in a fixed instant centre of rotation. All components were fixed using cement and the patellae were not resurfaced. The inserts were made of compression moulded ultra high molecular weight polyethylene. The mobile-bearing implant has a central guiding mechanism in the form of a ‘mushroom’ that fits into a slot of the polyethylene undersurface. During surgery 1 mm tantalum markers were inserted in predefined non-weight bearing areas of the mobile insert to visualize the polyethylene in the fluoroscopic images.

2.1. RSA

Roentgen stereophotogrammetric analysis (RSA) was used to determine the migration of the prosthesis with respect to the bone. During surgery, 6 to 8 tantalum markers (1 mm diameter) were inserted into the tibial metaphysic of each patient. The first RSA examination, two days after surgery and before mobilization, served as reference baseline. Subsequent evaluations of migration (6 and 12 months post-operatively) were related to the relative position of the prosthesis with respect to the bone at the time of the first evaluation. The precision of the RSA measurements was determined by means of double examinations at the 1 year follow-up.

2.2. Fluoroscopy

Single plane fluoroscopy was used to determine anterior–posterior translation and axial rotation of the insert and the femoral component with respect to the tibial component (super digital fluorography system, Toshiba Infinix, Toshiba, The Netherlands) (15 frames/sec, resolution 1024 × 1024, pulse width 1 ms). The patients were asked to perform three step-up and lunge motions (height 18 cm) with bare feet in front of a flat panel fluoroscope. Patients were instructed to keep their weight on the leg of interest. Fluoroscopic and RSA images were processed using a commercially available software package (Model-based RSA, Medis specials b.v., The Netherlands). Reverse engineered three-dimensional (3D) models of the components were used to assess the position and orientation of the components in the fluoroscopic images (Kaptein et al., 2003). RSA images were used to create accurate 3D models of the markers of the inserts to assess position and orientation of the insert in the fluoroscopic images. Fluoroscopy showed to have an accuracy of 0.3° and 0.3 mm (Garling et al., 2005a). At maximal extension, the axial rotation was defined to be zero. The minimal distance between the femoral condyles and the tibial base plate was calculated independently for the medial and lateral condyle. The lowest points of each frame were projected on the tibial plane to show the anterior–posterior motion and the pivot point of rotation of the femoral component with respect to the tibial component.

2.3. Statistical analysis

A paired two-tailed Student's *t*-test was used to compare the clinical scores, knee flexion ranges and anterior–posterior translation ranges between follow-ups. An independent Student's *t*-test was used for comparison between implant groups. Mean and standard deviations were presented. Because of the complexity of the data, due to different range of motions, different motion velocities and multiple trials, a linear mixed-effects model for longitudinal data was used to compare the differences between the axial rotation of the femoral component and the insert over the follow-ups. The model assumed a linear trend of axial rotation versus knee flexion angle within each follow-up. A patient random effect as well as a trial-within-patient nested random effect was incorporated in the model for both the intercept and slope coefficients of the linear trend. The first random effect was included to account for between-patient heterogeneity in observed differences, while the latter effect was included to take into account differences in the number of analysable trials per patient between follow-ups. It is a key characteristic of the model that differences in range of motion between trials are taken into account with respect to the fitting of the population linear effect within each follow-up. The model was fit using a fully Bayesian formulation via Markov chain Monte Carlo within the package

Table 1
Patient details. Mean (standard deviation) of age at surgery (years), body mass index (BMI), follow-up moment (FU) in months and pre- and post-operative knee society knee score (KS) and function score (FS) are presented for the mobile-bearing (MB), the fixed-bearing (FB) and the total group. The knee society knee scores and functions scores improved post-operatively significantly. Corresponding *P*-values are presented.

	Gender (male/female)	Age	BMI	FU I	FU II	Pre-operatively		FU I		FU II	
						KS	FS	KS	FS	KS	FS
MB	2/7	63 (9.6)	29.3 (6.7)	7 (1.5)	13 (1.1)	50 (19.5)	49 (12.2)	90 (4.3) $P = 0.000$	81 (25.9) $P = 0.005$	93 (1.9) $P = 0.000$	78 (16.9) $P = 0.001$
FB	5/6	66 (9.1)	29.6 (5.9)	6 (1.6)	12 (1.0)	43 (12.5)	52 (17.8)	89 (7.0) $P = 0.000$	77 (21.0) $P = 0.007$	92 (4.0) $P = 0.000$	73 (23.9) $P = 0.029$
Total	7/13	65 (9.2)	29.5 (6.1)	6 (1.5)	13 (1.1)	46 (15.9)	51 (15.2)	90 (6.0) $P = 0.000$	79 (22.4) $P = 0.000$	92 (3.3) $P = 0.000$	75 (20.8) $P = 0.000$

WinBUGS (Lunn et al., 2000). Model-based residuals were investigated to detect potential mismatch between the observed data and the assumed model, which could adversely affect conclusions. Based on the model, the fitted mean population linear trends were calculated for the rotation of the insert, the femoral component and the difference between them versus knee flexion angle, together with standard errors for each follow-up.

3. Results

Age at surgery, body mass index (BMI), pre- and post-operative KSS knee score and function score were not statistically different between the mobile-bearing and fixed-bearing group (Table 1). Knee scores and function scores significantly improved post-operatively in both groups. For the total group, the mean KSS knee score increased from 46 points pre-operatively to 90 points 6 months post-operatively ($P=0.000$) and the improvement remained 1 years post-operatively. The mean KSS function score increased from 51 points pre-operatively to 79 points at 6 months ($P=0.000$) and 75 points at 1 year post-operatively. None of the patients had a flexion contracture post-operatively or an extension lag. No clinical relevant deviations were observed in the post-operative alignment of the components.

3.1. RSA

The precision of the RSA measurements was determined by means of double examinations at the 1 year follow-up ($n=16$). There was no difference in precision between the mobile-bearing and fixed-bearing group. Significant rotations at the 95% significant level were >0.25° for anterior–posterior tilt, >0.5° for axial rotation and >0.15° for varus–valgus tilt. The values for significant translations were >0.06 mm for both medial–lateral translation and subsidence and >0.18 mm for anterior–posterior translation.

The 1 year post-operative RSA results showed considerable early migrations (>1° and >0.5 mm in one or more directions) in 3 out of 9 mobile-bearing patients and 1 out of 11 fixed-bearing patient (1 rheumatoid arthritis and 3 osteoarthritis patients, all women). In three of these patients, radiolucent lines were visible on the 1 year post-operative X-rays. The other patients had insignificant migrations below the measured threshold or stabilized after 6 months. The migrations were more prominent for the rotations than for the translations. Mean Maximum Total Point Motion (MTPM) at 1 year was 0.92 mm (SD: 0.92) for the total group 0.84 mm (SD: 1.03) for the fixed-bearing and 1.02 mm (SD: 0.81) for the mobile-bearing group. When the 4 patients with early migrations were not included in the MTPM, the MTPM decreased to 0.50 mm (SD: 0.29) for the total group, to 0.54 mm (SD: 0.33) for the fixed-bearing and 0.41 mm (SD: 0.15) for the mobile-bearing group.

3.2. Fluoroscopy

The mean range of knee flexion during the step-up and lunge motion was not significantly different for the mobile-bearing and fixed-bearing group and for FU1 and FU2 (Table 2, Figs. 1 and 2). Performing the step-up motion, all patients showed external rotation of the tibial component while extending, like expected. Performing the lunge motion, all the patients started with internal rotation of the tibial component while flexing the knee. Beyond 60° of knee flexion, external rotations were seen in all fixed-bearing patients and 50% of the mobile-bearing patients, ranging from returning to their starting position to 5° to 10° beyond their starting position.

3.3. Axial rotation mobile insert

Axial rotations of the mobile insert and femoral component were not significantly different during both follow-ups and both motions.

Table 2
Knee flexion range (°) and axial rotation range (°) of the femoral component (mean and standard deviation) for follow-up 1 (FU I) and follow-up 2 (FU II) for the mobile-bearing (MB), the fixed-bearing (FB) and the total group.

	Step-up				Lunge			
	Knee flexion		Axial rotation femoral component		Knee flexion		Axial rotation femoral component	
	FU I	FU II	FU I	FU II	FU I	FU II	FU I	FU II
MB	59.8 (11.4)	61.0 (13.5)	9.9 (4.6)	8.7 (3.7)	71.9 (19.7)	80.2 (13.9)	7.2 (2.2)	8.0 (3.1)
FB	58.0 (8.2)	59.9 (7.0)	7.6 (2.2)	8.4 (2.8)	78.4 (13.6)	82.2 (17.3)	6.2 (2.3)	6.6 (2.7)
Total	58.8 (9.7)	60.4 (10.2)	8.6 (3.6)	8.5 (3.2)	75.6 (16.7)	81.4 (15.9)	6.6 (2.3)	7.2 (2.9)

Hence, the mobile insert was following the femoral component during motion. Despite this fact, medial, lateral and central pivot points of rotations of the femoral component with respect of the tibial component were measured, whereas a central pivot point of rotation was expected according to design. The range of axial rotation of the mobile insert did not change with follow-ups. The axial rotation during the step-up motion was 9.3° (SD: 4.5°) and 8.0° (SD: 4.8°), respectively for FU1 and FU2. During the lunge motion axial rotation of the insert was 6.6° (SD: 4.0°) and 7.0° (SD: 3.1°) for respectively FU1 and FU2.

3.4. Anterior–posterior translation

For both the step-up and lunge motion, the range of anterior–posterior translation of the medial condyle did not change with follow-ups and was not different between mobile-bearing and fixed-bearing groups (Table 3). For the lateral condyle, the range of translation was significantly larger for the fixed-bearing group during the lunge motion at 6 months (7.1 mm versus 5.8 mm, $P=0.024$) and during the step-up motion at 12 months (7.2 mm versus 6.0 mm, $P=0.031$).

For each individual patient, the patterns of anterior–posterior translation were essentially the same 6 months and 1 year post-operatively. The lateral condylar translations were anterior throughout knee extension and medial condylar translations posterior. In the mobile-bearing group, one patient showed atypical translations while performing the step-up motion, namely posterior translation of both condyles during extension. Throughout flexion, the lateral condyle was expected to move posterior and the medial condyle anterior or in case of no or minimal axial rotation both condyles were expected to move posterior.

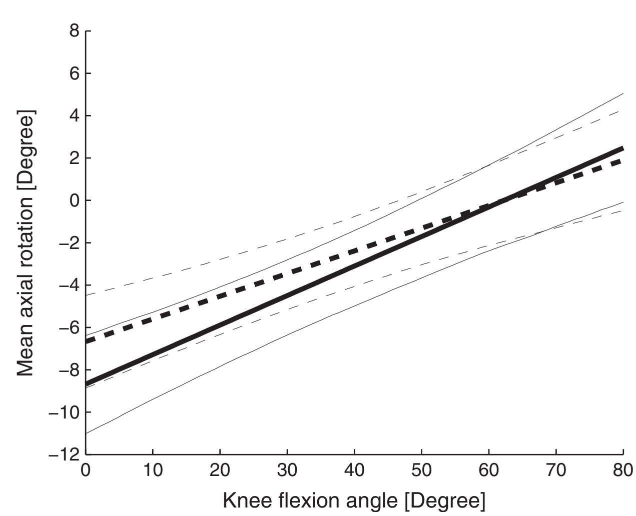

Fig. 1. Mean axial rotation of the femoral component and confidence intervals for the step-up motion for the mobile-bearing group (solid) and the fixed-bearing group (dotted) at follow-up 1.

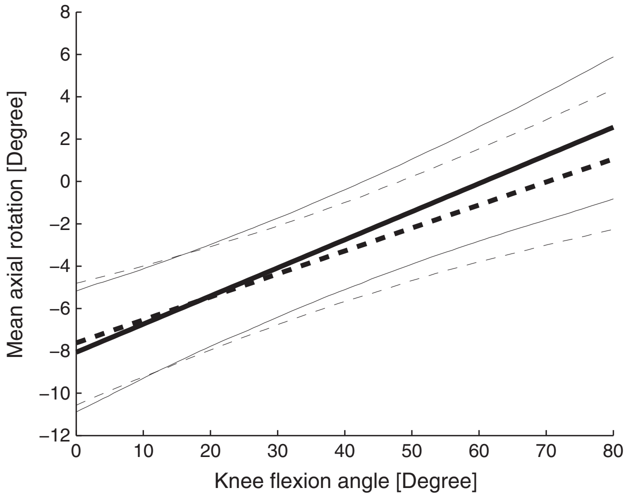

Fig. 2. Mean axial rotation of the femoral component and confidence intervals for the step-up motion for the mobile-bearing group follow-up 1 (solid) and follow-up 2 (dotted).

However, 63% of the mobile-bearing group and 27% of the fixed-bearing group showed anterior translation of both condyles during flexion.

4. Discussion

The aim of this study was to evaluate and compare kinematics as well as early migration of the tibial component of a mobile-bearing and fixed-bearing total knee prosthesis of the same single-radius design. The mobile-bearing and fixed-bearing group showed approximately the same range of knee flexion and axial rotation of the femoral component with respect to the tibial component. Hence, the mobile-bearing variant did not add additional mobility to the knee joint which could be assumed based on theoretical grounds. The additional mobility was not necessary during the range of motion of the functional tasks performed in this study.

For the lateral condyle, the range of translation was significantly larger for the fixed-bearing group during the lunge motion at 6 months and during the step-up motion at 12 months. This means that the mobile-bearing group had a smaller sliding distance and therefore a reduced surface area of polyethylene being worn. The anterior–posterior translation in this study was assessed by the lowest points of the femoral condyles with respect to the tibial component. In determining the anterior–posterior translations, the motion of the insert in the mobile-bearing group was not taken into account. Because the mobile insert followed the femoral component during motion, the actual sliding of the condyles in the mobile-bearing group is even smaller. However, more paradoxical anterior–posterior translations were seen in the mobile-bearing group compared to the fixed-bearing group during the dynamic tasks. Throughout knee flexion both condyles translated anterior instead of posterior. Lack of engagement of the cam-post mechanisms in activities that require less flexion could explain these paradoxical motions. Paradoxical motions are assumed to increase wear (Banks and Hodge, 2004; Benedetti et al., 2003; Krichen et al., 2006; Taylor and Barrett, 2003; van Duren et al., 2007).

Medial, lateral and central pivot points of axial rotation of the femoral component with respect to the tibial component were found. Because of the centrally located trunnion in the mobile-bearing variant, a centrally located pivot point of rotation was expected. The medial and lateral pivot points may be caused by low congruency between the insert and femoral component and by laxity of the surrounding ligaments (Banks and Hodge, 2004). No manifest laxity was seen in these patients.

In several RSA studies evaluating other total knee prostheses, initial migration was seen during the first 3 to 6 months. After this period the components tend to stabilize (Therbo et al., 2008; van der Linde et al., 2006). The preliminary RSA data of this study confirm early migration and latter stabilization of the tibial component in most patients. The larger MTPM of the mobile-bearing group imply that the mobile insert does not improve initial fixation of the prosthesis to the bone, as intended by mobile-bearing designs. Additionally, early migration in 3 out of 9 mobile-bearing patients versus 1 out of 11 fixed-bearing patients indicates that early migration of the tibial component is worse in the mobile-bearing group. Until now, patients did not have clinical symptoms. However, it seems reasonable to consider that continuation of the large initial migration seen in 4 patients might develop into clinical loosening and become of clinical significance. RSA evaluations of all patients will continue at yearly intervals to determine the long-term fixation of the components in the bone.

Comparable studies are not able to prove or disprove the theoretical working principle of mobile-bearing designs or find significant differences in clinical or radiological outcomes (Breugem et al., 2008; Callaghan, 2001; Haider and Garvin, 2008; Huang et al., 2007; Jacobs et al., 2001; Oh et al., 2008; Post et al., 2010; Rossi et al., 2009; Smith et al., 2010; van der Bracht et al., 2010). In this study, the fixed-bearing knee performed as good as the mobile-bearing knee and maybe even slightly better based on less paradox and reversed motions and less early migrations. Retrieval studies showing wear patterns and particles (sizes) and large, long-term RSA studies assessing the effect of prosthesis–bone interface stresses on migration of the components should be combined with kinematic studies to clarify differences in design variations and the benefit of on prosthesis above another. If no superiority of one of the designs concerning revision rate, survival and outcome can be found, one might question the added value of a mobile-bearing knee taking into account the added costs, complexity for implantation and persisting concerns about dislocation and breakage of the polyethylene insert (Callaghan, 2001; Hanusch et al., 2010; Pagnano and Menghini, 2006). Development and use of improved wear resistant triple cross linked polyethylene for fixed-bearing total knees might be preferred over the use of mobile-bearing knees. These inserts will limit wear that occurs during sliding of the femur on the tibial articulating surface.

Table 3
Range of anterior–posterior translation (mean and standard deviation in mm) of the medial and lateral condyle for follow-up 1 (FU I) and follow-up 2 (FU II) for the mobile-bearing (MB), the fixed-bearing (FB) and the total group.

	Anterior–posterior translation							
	Step-up				Lunge			
	Medial condyle		Lateral condyle		Medial condyle		Lateral condyle	
	FU I	FU II	FU I	FU II	FU I	FU II	FU I	FU II
MB	7.1 (2.7)	6.7 (2.2)	6.5 (1.9)	6.0 (2.1)	8.4 (2.9)	8.0 (3.0)	5.8(2.0)	6.9(2.0)
FB	6.4 (2.1)	6.6 (1.7)	6.5 (2.1)	7.2* (2.0)	7.5 (2.5)	7.5 (3.0)	7.1** (1.9)	7.5 (1.8)
Total	6.7 (2.4)	6.6 (1.9)	6.5 (2.0)	6.6 (2.1)	7.9 (2.7)	7.7 (3.0)	6.5 (2.1)	7.3 (1.9)

*$P=0.031$
**$P=0.024$

5. Conclusion

Despite the mobile insert following the femoral component during motion, and therefore performing as intended, no kinematic advantages of the mobile-bearing total knee prosthesis were seen. The fixed-bearing knee performed as good as the mobile-bearing knee and maybe even slightly better based on less paradox and reversed motions and less early migrations.

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