

## No differences in in vivo kinematics between six different types of knee prostheses

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### Abstract

**Purpose** The aim of this study was to compare a broad range of total knee prostheses with different design parameters to determine whether in vivo kinematics was consistently related to design. The hypothesis was that there are no clear recognizable differences in in vivo kinematics between different design parameters or prostheses.

**Methods** At two sites, data were collected by a single observer on 52 knees (49 subjects with rheumatoid arthritis or osteoarthritis). Six different total knee prostheses were used: multi-radius, single-radius, fixed-bearing, mobile-bearing, posterior-stabilized, cruciate retaining and cruciate sacrificing. Knee kinematics was recorded using fluoroscopy as the patients performed a step-up motion.

**Results** There was a significant effect of prosthetic design on all outcome parameters; however, post hoc tests showed that the NexGen group was responsible for 80% of the significant values. The range of knee flexion was much smaller in this group, resulting in smaller anterior-posterior translations and rotations.

**Conclusion** Despite kinematics being generally consistent with the kinematics intended by their design, there were no clear recognizable differences in in vivo kinematics between different design parameters or prostheses.

Hence, the differences in design parameters or prostheses are not distinct enough to have an effect on clinical outcome of patients.

**Level of evidence** Therapeutic study, Level III.

**Keywords** Kinematics · Fluoroscopy · Single-radius · Multi-radius · Mobile-bearing · Fixed-bearing

### Introduction

Many studies have characterized the in vivo motions of total knee prostheses. Major conclusions are that there is a broad range of kinematics and that specific prostheses have specific advantages and disadvantages [2, 5, 27]. For example, posterior-stabilized knee prostheses were developed to prevent reversed anterior translations of the femoral condyles during flexion seen in cruciate sacrificing prostheses. The induced posterior displacement will avoid impingement and thereby improve the range of motion of the knee [16]. However, it is no exception that the actual in vivo kinematics of knee prostheses is not in line with the desired kinematics as intended by the design. Understanding the effect of design choices on in vivo kinematics, stability and muscle activation has become more important because of the increasingly clear connection between knee prosthesis kinematics and clinical performance. Therefore, the aim of this study was to compare a broad range of total knee prostheses with different design parameters (multi-radius, single-radius, fixed-bearing, mobile-bearing, posterior-stabilized, cruciate retaining and cruciate sacrificing) to determine whether in vivo kinematics was consistently related to design. The hypothesis was that there are no clear recognizable differences in in vivo kinematics between different design parameters or prostheses.

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## Materials and methods

At two sites, data were collected by a single observer on 52 knees (49 subjects with rheumatoid arthritis or osteoarthritis). Six different total knee prostheses were used (Table 1). Total knee replacements were performed by five surgeons at three hospitals in two countries (the Netherlands and United Kingdom). All surgeons were specialized in total knee arthroplasty, and prostheses were implanted according to the operative techniques described by the manufacturer. Based on a previous fluoroscopy study, relative motions of  $0.3^\circ$  could be detected when ten patients were included in each group [13]. Knee kinematics was recorded using fluoroscopy as the patients performed a step-up motion. The experimental set-up was the same for all patients. Patients' reported functional ability (knee score and function score) was quantified pre- and post-operatively for the prospective patients using the Knee Society Score (KSS) [11]. The study was approved by the respective local medical ethics committees, and all patients gave informed consent.

### Fluoroscopy

The patients were asked to perform a step-up motion (height 18 cm) with bare feet in front of a flat panel fluoroscope (15 frames/sec, resolution  $1,024 \times 1,024$ , pulse width  $<3.2$  ms). Patients were instructed to keep their weight onto the leg of interest and to perform the motions in a controlled manner. Three-dimensional (3D) models (reverse engineered or computer aided design) of the tibial and femoral components were used to assess the position and orientation of the components in the fluoroscopic images [17]. In case of a mobile-bearing prosthesis, during surgery 1 mm tantalum markers were inserted in predefined non-weight bearing areas of the mobile insert to visualize the polyethylene. Roentgen stereophotogrammetric analysis (RSA) was used to create accurate 3D models of the markers of the inserts to assess position and orientation of the mobile insert in the fluoroscopic images. This technique showed to have an axial rotation accuracy of  $0.1^\circ$  and 0.1 mm [17]. The coordinate system was defined as the local coordinate system of the tibial component. At maximal extension, the axial rotation is defined as zero. The minimal distance between the femoral condyles and the tibial base plate was calculated independently for the medial and lateral condyle and projected on the tibial plane to show the anterior-posterior motions. This line was projected onto the transverse plane of the tibial plateau for each fluoroscopic frame. All images were processed using a commercially available software package (Model-based RSA, Medis specials b.v., Leiden, The Netherlands).

### Statistical analysis

A chi-square test (Cramer's V) was used to test whether the prosthesis groups were different on variables, such as age, gender, BMI and functional and knee scores. An ANOVA was used to test for differences in outcome variables among the prosthetic groups. Levene's test was used to test for homogeneity of variances between prosthetic groups. For femoral axial rotation ( $P = 0.006$ ) and insert axial rotation ( $P = 0.001$ ), the variances were not equal. To correct for this unequal variance and to correct for the different group sizes, Brown-Forsythe correction was used. When a significant effect of prosthetic design on an outcome variable was found, post hoc tests were performed to test which groups were different.

## Results

Age at surgery, BMI, pre-operative KSS knee score and function score did not differ significantly between groups (Table 1). The PFC-Sigma patients had no pre- or post-operative scores. The Duracon patients were included retrospectively. Therefore, no pre-operative clinical scores were available. There was no difference in post-operative KSS function score between groups. However, there was a small significant difference in post-operative KSS knee score ( $P = 0.045$ ). Post-operatively, the Duracon patients (multi-radius fixed-bearing cruciate retaining) scored highest on both KSS function score and knee score. In all groups, the KSS function score and knee score increased post-operatively. All patients were considered clinically successful without significant pain or measurable ligamentous instability. Also, no clinical deviations were reported, such as extension lags or flexion contractures.

### Knee flexion angle

The NexGen group had significant smaller knee flexion angles compared to the other prosthetic groups (Triathlon MB  $P = 0.005$ ; Triathlon FB  $P = 0.004$ ; Duracon  $P = 0.003$ ; ROCC  $P = 0.007$ ; PFC-Sigma  $P = 0.017$ ). There were no significant differences between the other groups (Table 2).

### Axial rotation

The NexGen group had significantly smaller femoral axial rotation compared to the Duracon group ( $P = 0.000$ ), the Triathlon MB group ( $P = 0.024$ ) and Triathlon FB group ( $P = 0.001$ ). There were no differences in axial femoral rotation between the rest of the groups. The mean range of axial rotation of the insert of the NexGen patients was also

**Table 1** Overview of the prostheses used, congruency of the insert and number of knees and patient characteristics (mean and standard deviation)

Prosthesis	Design parameters	Number of knees	Follow-up (months)	Male/female	Age (years)	BMI (kg/m <sup>2</sup> )	Pre-operative		Post-operative	
							Function score	Knee score	Function score	Knee score
Duracon <sup>a</sup>	Multi-radius Fixed-bearing Cruciate retaining	10	21 (8.9)	3/7	68 (10.9)	29 (3.7)	x	x	88 (13)	95 (3)
Triathlon FB <sup>a</sup>	Single-radius Fixed-bearing Posterior-stabilized	11	13 (1.0)	5/6	66 (9.1)	30 (6.2)	52 (18)	43 (13)	73 (24)	92 (4)
Triathlon MB <sup>a</sup>	Single-radius Mobile-bearing Posterior-stabilized	9	12 (2.5)	2/7	63 (9.6)	31 (7.5)	48 (13)	49 (21)	71 (26)	90 (11)
PFC-Sigma <sup>b</sup>	Multi-radius Fixed-bearing Posterior-stabilized	8	5 (1.0)	4/4	67 (7.6)	31 (5.1)	x	x	x	x
NexGen <sup>c</sup>	Multi-radius Mobile-bearing Posterior-stabilized	7	43 (7.7)	1/6	67 (8.2)	30 (3.1)	43 (16)	44 (24)	74 (30)	84 (18)
ROCC <sup>d</sup>	Multi-radius Mobile-bearing Cruciate sacrificing	7	25 (0.8)	3/4	63 (10.9)	29 (5.6)	50 (26)	47 (12)	79 (22)	86 (11)

Missing data are indicated with an 'x'

<sup>a</sup> Stryker, Kalamazoo, MI, USA

<sup>b</sup> DePuy Orthopaedics Inc., Warsaw, In, USA

<sup>c</sup> Zimmer Inc., Warsaw, In, USA

<sup>d</sup> Biomet, Europe BV, Dordrecht, The Netherlands

significantly smaller (limited to 2.0°) than the mean range of axial rotations of the inserts of the Triathlon MB and ROCC groups ( $P = 0.010$  and  $P = 0.006$ , respectively). There was no difference in axial insert rotation between the Triathlon and ROCC group. The mobile insert of the ROCC followed the motion of the femoral component until approximately 60° of knee flexion. Beyond 60° of knee flexion, 3 of 7 ROCC patients showed paradoxical axial rotations. The insert of the Triathlon patients followed the femoral component during the complete motion (maximum knee flexion during step-up was 80°), without showing paradoxical axial rotations.

#### Pivot point of rotation

Under the assumption that the inserts will follow the femoral component, a centrally located pivot point of axial rotation of the femoral component was expected. In all groups, except for the ROCC patients, the measured pivot point of axial rotation varied between a medial, central or lateral position. All the ROCC patients had a central point

of rotation, except for one subject having a medial pivot point of axial rotation (Fig. 1).

#### Anterior-posterior translation of the contact points

The translations of the lateral condylar were essentially anterior throughout knee extension and translations of the medial condylar mainly posterior. The ROCC patients showed most reversed anterior-posterior motions. Six of seven patients had paradoxical motions at some point. One Triathlon MB patient had paradoxical motion, namely posterior translation during extension. The NexGen, Duracon, PFC-Sigma and Triathlon FB patients showed no paradoxical anterior-posterior motions. The Duracon group had larger translations of the medial condyle compared to the PFC-Sigma group ( $P = 0.021$ ) and the NexGen group ( $P = 0.005$ ) and of the lateral condyle compared to the Triathlon MB group ( $P = 0.015$ ) and NexGen group ( $P = 0.003$ ). Between the rest of the groups, there were no significant differences in anterior-posterior translation.

**Table 2** Mean and standard deviation of the range of knee flexion (°), axial rotation of the femoral component and the insert (°) and anterior-posterior (AP) translation (mm) of the lateral and medial condyle during the step-up motion for each prosthetic group

Prosthesis	Knee flexion (°)	Axial rotation (°)		AP translation (mm)	
		Femoral component	Mobile insert	Medial condyle	Lateral condyle
Duracon	59.7 (9.3)	8.6 (2.3)	–	9.0 (2.1)	11.1 (3.4)
Triathlon FB	60.3 (5.4)	8.3 (2.7)	–	6.6 (1.5)	7.1 (1.8)
Triathlon MB	62.0 (12.9)	9.6 (4.3)	8.7 (4.9)	6.8 (2.0)	6.0 (1.6)
PFC-Sigma	56.5 (9.9)	8.3 (4.5)	–	5.3 (1.9)	6.8 (2.5)
NexGen	34.5 (10.3)	3.0 (0.5)	2.0 (0.7)	3.9 (2.1)	4.8 (1.8)
ROCC	59.0 (8.8)	10.4 (5.4)	7.3 (2.8)	6.9 (2.0)	7.0 (1.5)
Levene's test	0.83 n.s.	3.80 $P = 0.006$	9.60 $P = 0.001$	0.31 n.s.	1.74 n.s.
ANOVA Brown-Forsythe	$F(5, 36.7) = 8.38$ $P = 0.000$	$F(5, 25.1) = 3.56$ $P = 0.014$	$F(2, 13.2) = 9.11$ $P = 0.003$	$F(5, 40.7) = 6.46$ $P = 0.000$	$F(5, 34.6) = 8.55$ $P = 0.000$

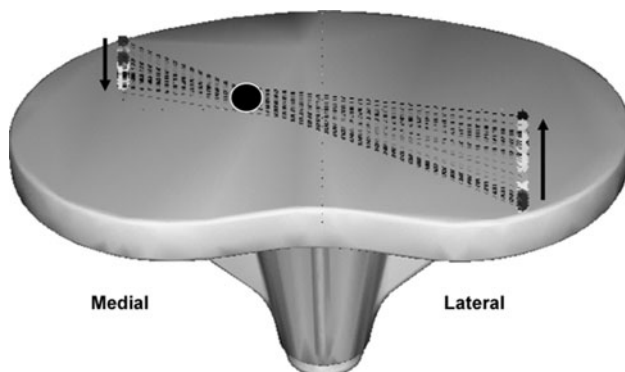
Also, the results of the Levene's test and ANOVA are presented. There was a significant effect of prosthetic design on all outcome variables

–: Fixed-bearing prosthesis; therefore, no 'mobile insert' data

n.s. Not significant

## Discussion

The aim of this study was to compare different total knee prostheses (multi-radius, single-radius, fixed-bearing, mobile-bearing, posterior-stabilized, cruciate retaining and cruciate sacrificing) to determine whether in vivo kinematics is consistently related to kinematics intended by the knee prosthesis design. According to several authors, in vivo knee kinematics after total knee arthroplasty is directly related to the constraints of the design of the prosthesis [4, 5, 9]. On the other hand, several studies found aberrant and highly unpredictable kinematics, and there was no distinction in clinical results and kinematics between different types of prostheses [9, 14, 15, 20, 22–24]. This study showed that despite kinematics being generally consistent with the kinematics intended by their design, there were no clear recognizable differences in in vivo kinematics between different design parameters or prostheses.



**Fig. 1** Example of a medial pivot point of axial rotation. The medial condyle moves to posterior and the lateral condyle to anterior during knee extension

Patients with a cruciate sacrificing prosthesis (ROCC) cannot rely on the cruciate ligaments to provide stability. To compensate for this, the congruency of the insert is increased, providing more intrinsic stability between the insert and the femoral component. The increased congruency is also expected to lead to increased axial rotation of the mobile insert. This is supported by our fluoroscopic data, showing that the insert was following the femoral component until approximately 60° of knee flexion. Beyond 60° of knee flexion, diversion between the insert and the femoral component and reversed axial rotations occurred. Despite the lower congruency, the Triathlon MB group showed equal motion of the insert and femoral component during the whole range of flexion, without occurrence of reversed axial rotations. This suggests a more uniform motion in this group. A more uniform motion may reduce wear of the polyethylene, due to a reduction in shear forces at the liner interface [6, 19].

According to knee simulator studies, the reduction in sliding distance reduces the surface area of polyethylene being worn which in turn reduces wear [18, 19]. The cruciate retaining group (Duracon) had the largest anterior-posterior motions, without revealing any reversed femoral tibial motion patterns. This is in accordance with the intended kinematics, keeping the posterior ligament to preserve normal rollback. The retained posterior ligament is assumed to increase joint stability compared to cruciate sacrificing total knees. This assumption is supported by the Duracon group having the highest post-operative KSS knee and function scores. Possibly, this patient group had also better function pre-operatively. Pre-operative scores and function are good indicators for post-operative scores and functions. Unfortunately, pre-operative scores were not quantified for these patients.

All total knees showed comparable axial rotations of the femoral component with respect to the tibial component, except for the NexGen patients. The mobile inserts did not add additional mobility to the knee joint compared to the fixed-bearing groups. However, additional mobility was possibly not needed during the step-up motion performed. The inserts of two of the three mobile-bearing groups moved as predicted on theoretical grounds. The absence or reduced mobility in the NexGen patients makes this implant very similar to a fixed-bearing prosthesis. This absence or reduced mobility will also enhance wear of the polyethylene and could induce a higher incidence of loosening by transmitting larger forces to the bone-implant interface [1, 6, 7, 10, 12, 25, 26].

In all three mobile-bearing prostheses used, the centrally located trunnion imposed a centrally located pivot point of rotation of the insert on top of the tibial plateau. Under the assumption that the inserts will follow the femoral component, a centrally located pivot point of axial rotation of the femoral component was expected. Only the ROCC patients had a measured central pivot point of axial rotation of the femoral component with respect to the tibial component. In the other two mobile-bearing groups, patients showed also medial and lateral pivot points of axial rotation. These deviant pivot points might be caused by low congruency between the insert and femoral component and by laxity of the surrounding ligaments [4]. However, no manifest laxity was seen in these patients.

A possible limitation of this and other multicenter studies, which could explain the variability in kinematics, is patient diversity (osteoarthritis and rheumatoid arthritis), pre-operative deformities, muscle adaptations and the different surgeons [3]. It is known that surgeons are still the biggest variable in outcome after total knee arthroplasty. Factors that play a major role in dysfunction of any knee and are determined by the surgeon are frontal plane malalignment, axial malrotation of the prosthesis, sagittal overstuffing of the knee, inappropriate level of joint space, inappropriate constraint or ligamentous imbalance and poor initial fixation of the implant [3, 8, 21].

Statistics showed that there was a significant effect of prosthetic design on all outcome parameters; however, post hoc tests showed that the NexGen group was responsible for 80% of the significant values. In this group, the range of knee flexion was much smaller, resulting in smaller anterior-posterior translations and rotations. It is not clear whether and why this patient group performed the step-up task differently.

This study showed that the in vivo kinematics of most included total knee prostheses were consistent with the kinematics intended by their design. However, some prostheses showed reversed or paradoxical kinematics in some parts of their functional range of motion. If the

theoretical kinematics is not in accordance with the in vivo kinematics, the manufacture should optimize the new prosthetic design to prevent large scale polyethylene wear with subsequent prosthesis loosening. This is of importance because of the growing population of younger patients who will require an implant to function for at least two decades. Because of the high accuracy, it is recommended that fluoroscopy is used for evaluating the kinematics of new total knee prostheses before introducing the new knee worldwide on the market.

## Conclusion

Despite kinematics being generally consistent with the kinematics intended by their design, there were no clear recognizable differences in in vivo kinematics between different design parameters or prostheses. Hence, the differences in design parameters or prostheses are not distinct enough to have an effect on clinical outcome of patients.

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