Clin Orthop Relat Res (2012) 470:1860–1868
DOI 10.1007/s11999-012-2248-0

Clinical Orthopaedics and Related Research®
A Publication of The Association of Bone and Joint Surgeons®

SYMPOSIUM: RETRIEVAL STUDIES

Knee Wear Measured in Retrievals

A Polished Tray Reduces Insert Wear

Daniel J. Berry MD, John H. Currier MS, Michael B. Mayor MD, John P. Collier DE

Published online: 8 February 2012

Abstract

Background Polyethylene wear is often cited as the cause of failure of TKA. Rotating platform (RP) knees show notable surface damage on the rotating surface raising concerns about increased wear compared to fixed bearing inserts.

Questions/purposes We therefore addressed the following questions: Is wear in RP inserts increased compared to that in fixed bearing inserts? Does the surface roughness of the tibial tray have a measurable impact on in vivo wear of modular knees? And does wear rate differ between posterior stabilized (PS) and cruciate retaining (CR) knees?

Methods We compared wear in two series of retrieved knee devices: 94 RP mobile bearings with polished cobalt-chrome (CoCr) trays and 218 fixed bearings with both rough titanium (Ti) and polished CoCr trays. Minimum implantation time was 0.4 months (median, 36 months; range, 0.4–124 months) and 2 months (median, 72 months; range, 2–179 months)
for the RP and fixed bearing series, respectively.

Results Wear rate was lower for RP inserts than for fixed bearing inserts. Backside wear rate was lower for fixed bearing inserts mated to polished CoCr trays than for inserts from rough Ti trays. Inserts against polished trays (RP or fixed bearing) showed no increase in wear rate increase over time. Wear rate of PS knees was similar to that of CR knees.

Conclusions We found mobile bearing knees have reduced wear rate compared to fixed bearings, likely due to the polished CoCr tibial tray surface. Fixed bearing inserts in polished CoCr trays wear less than their counterparts in rough Ti trays, and the wear rate of inserts from polished CoCr trays does not appear to increase with time.

One of the authors (DJB) certifies that he has or may receive payments or benefits, in any one year, an amount in excess of $100,000 from a commercial entity (DePuy Orthopaedics, Inc, a Johnson and Johnson company, Warsaw, IN, USA) related to this work; one of the authors (MBM) certifies that he has or may receive payments or benefits, in any one year, an amount in excess of $10,000 from a commercial entity (DePuy Orthopaedics, Inc) related to this work; one of the authors (JPC) is a consultant from a commercial entity (DePuy Orthopaedics, Inc) related to this work; the institution of two of the authors (MBM, JPC) has received funding from a commercial entity (DePuy Orthopaedics, Inc) related to this work.
All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research* editors and board members are on file with the publication and can be viewed on request.

This work was performed at the Dartmouth Biomedical Engineering Center, Hanover, NH, USA.

D. J. Berry
Department of Orthopaedic Surgery, Mayo Clinic, Rochester, MN, USA

J. H. Currier, M. B. Mayor, J. P. Collier (✉)
Dartmouth Biomedical Engineering Center, Thayer School of Engineering, Dartmouth College, 8000 Cummings Hall, Hanover, NH 03756, USA
e-mail: john.p.collier@dartmouth.edu

Introduction

Polyethylene wear frequently is cited by orthopaedic surgeons as the cause of failure and revision of knee arthroplasty devices [27, 35, 38]. In modular knee bearings, backside wear can produce small debris particles of the size implicated as the cause of osteolysis [30, 33, 38]. Previous studies have documented the effect of backside wear on the locking mechanisms for different modular knee systems, leading to increased bearing motion within the tray and resultant bearing wear [11, 17, 31, 32].

Mobile bearing knees are an appealing approach to tibial loosening in fixed bearing knees presumably related to rotational malalignment [9, 15, 16]. Knee arthroplasties with rotating tibial platforms (RPs) represent one approach for mobile bearing devices [6]. A potential disadvantage of the RP knees is the addition of the large backside articular surface that accommodates tibiofemoral rotation. The concerns about backside wear being a source of wear debris in knees extend to RP knees and warrant careful study of their wear performance.

Recent reports on clinical wear performance of RPs that are based on visual assessment of damage to bearing surfaces have highlighted concern about backside wear based on the surface features seen [20, 22, 28]. Accurate measurement of actual material loss from retrieved knee bearings presents difficult challenges because gravimetric methods are not useful with retrievals and unworn reference dimensions are often unavailable. Through our ongoing retrieval collaboration that receives devices from many surgeons and institutions, we now have a series of knee retrievals for which as-manufactured dimensions are available and quantitative measurements of true knee wear can be determined.

We therefore addressed the following questions: (1) Is wear associated with RP mobile bearing inserts decreased compared to that of fixed bearing inserts? (2) Does the surface roughness of the tibial tray have a measurable impact on in vivo wear of modular knees? And (3) does wear rate differ between posterior stabilized (PS) knees and cruciate retaining (CR) knees?

Materials and Methods

This study is based on explanted devices sent for evaluation to an established retrieval laboratory open to submittal from all surgeons and centers. We investigated two series of retrieved knee devices: (1) 94 Sigma® RP mobile bearing knees (DePuy Orthopaedics, Inc, a Johnson and Johnson company, Warsaw, IN, USA) submitted by 26 surgeons between December 2002 and February 2011; and (2) 218 Sigma® fixed bearing knees (DePuy Orthopaedics, Inc) submitted by 46 surgeons between January 2003 and February 2011 (Table 1). The RP series included 27 inserts of the curved design (which is CR) and 67 inserts of the PS design. The fixed bearing series included 19 inserts with the posterior lipped design (which is CR), 85 of the curved design (CR), and 77 of the PS design. The fixed bearing knee series was also partitioned into 181 knees with rough (grit-blasted finish) titanium (Ti) trays (median implantation time, 81 months) and 37 with polished cobalt-chrome (CoCr) trays (median implantation time, 17 months). For the RP series, minimum implantation time was 0.4 months (median, 36 months; range, 0.4–124 months). For the fixed bearing series, minimum implantation time was 2.1 months (median, 72 months; range, 2.1–179 months). The polyethylene in the Sigma® fixed bearing series in rough Ti trays and the Sigma® RP series were made from compression-molded sheet stock of 1020 UHMWPE resin, gamma irradiated at approximately 4 Mrad and barrier packaged. The Sigma® fixed bearing series in polished CoCr trays had 10 inserts made from this same

Table 1. Knee retrieval series

Insert type	Number of retrievals			In vivo duration (months)	
	Total	Ti tray	CoCr tray	Median	Range
Sigma® RP					
Curved (CR)	27		27	37	0.4–109
PS	67		67	34	2–124
Total RPs	94		94	36	0.4–124
Sigma® fixed bearing Ti trays					
Posterior lipped (CR)	19	19		72	10–164
Curved (CR)	85	85		90	6–179
PS	77	77		76	2–164
Total Ti tray	181	181		81	2–179
Sigma® fixed bearing CoCr trays					
Posterior lipped (CR)	4		4	12	4–24
Curved (CR)	12		12	16	5–25
PS	21		21	24	4–47
Total CoCr tray	37		37	17	4–47
Total fixed bearing	218	181	37	72	2–179

Ti = titanium; CoCr = cobalt-chrome; RP = rotating platform; CR = cruciate retaining; PS = posterior stabilized.

compression-molded sheet stock of 1020 UHMWPE resin, gamma irradiated at approximately 4 Mrad and barrier packaged, and 27 inserts made from compression-molded sheet stock of 1020 UHMWPE resin, gamma irradiated at approximately 5 Mrad, heated to melt temperature, and sterilized with gas plasma. We included all explanted bearings of the Sigma® and Sigma® RP designs received during the study period in this study except those that had been autoclaved.

We estimated the total through-thickness wear of each insert by measuring the minimum thicknesses within the medial and lateral condylar bearing areas using a dial indicator with 3-mm-radius ball end contacts (Fig. 1). Wear penetration was calculated by subtracting the measured thickness dimension from the as-manufactured dimension. A composite through-thickness wear for each device was determined by the average of the wear on the medial and lateral bearing areas.

On the fixed bearing inserts, an estimate of backside wear was possible because their design incorporated topside datum surfaces that normally remain undamaged and unworn in vivo. The RP bearings in this study did not incorporate any flat topside datum surfaces so no reliable measurement of backside wear could be made. We measured the thickness of the polyethylene inserts from topside reference points to the bottom surface using dial calipers and a dial indicator (Fig. 2). Design drawings were used to obtain the nominal initial thickness at the corresponding measurement points, and backside wear depth was estimated by subtracting measured thickness from design thickness. The composite backside wear depth for an insert was calculated by linear interpolation of the wear depth at each measurement point to the center point of the backside area. To estimate the volume of backside wear, the composite backside wear depth was multiplied by the backside surface area (Fig. 3).

We measured five nonimplanted fixed bearing inserts and one nonimplanted RP insert to confirm reference dimensions.

We determined the dependence of wear rate on in vivo duration for each series by calculating Spearman's rho. The test for differences in medial and lateral wear was determined using the paired-samples t-test with a CI of 95%. We determined differences in wear rates between the RP and fixed bearing knees, between fixed bearings from Ti trays and fixed bearings from CoCr trays, and between CR and PS bearings using the independent-samples t-test for equality of means with a CI of 95% and equal variances assumed. The statistical package used was SPSS® Version 19 (IBM Corp, Chicago, IL, USA).

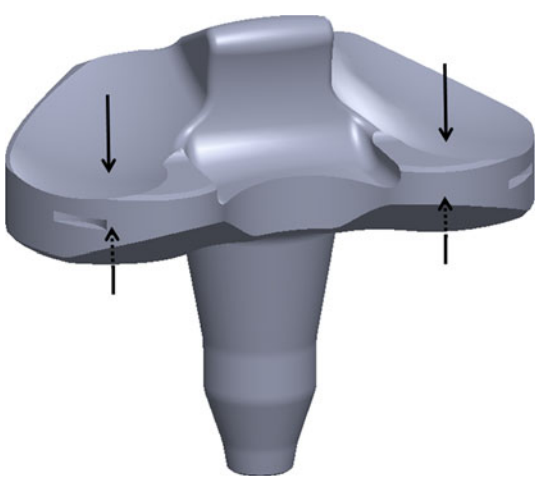

Fig. 1 Through-thickness wear of each insert (RP shown here) was determined by measuring the thickness of the retrieved knee bearings with a dial indicator at their thinnest point on both the medal and lateral condylar bearing areas, respectively (approximate locations indicated by arrows), and comparing those dimensions to the specified minimum thickness from the manufacturer's design drawings.

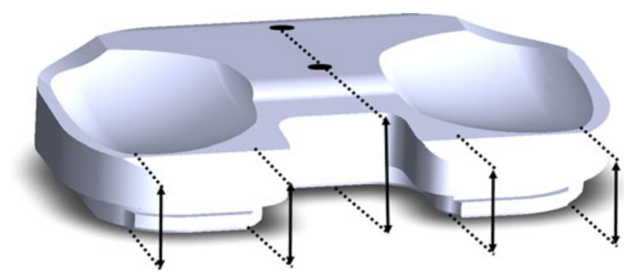

Fig. 2 For backside wear estimates on Sigma® fixed bearing inserts, thickness dimensions were taken at reference points indicated by the arrows on this schematic, which typically show no proximal surface wear, with care taken to measure perpendicular to the surface planes.

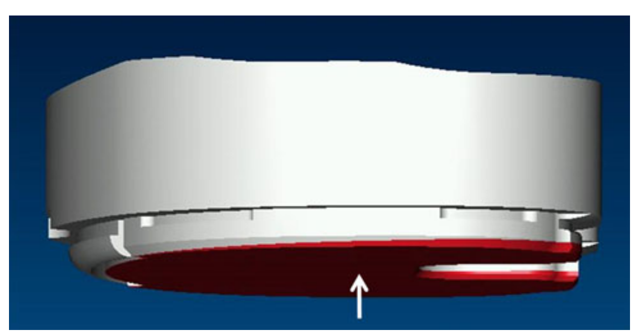

Fig. 3 Composite backside wear depth of fixed bearing inserts was determined taking multiple measurements and interpolating to wear at the center of insert (arrow). Inserts in rough Ti trays typically demonstrated a backside wear wedge, with more wear posteriorly and medially. Backside wear volume was calculated by multiplying the composite wear depth by the backside area.

Results

A total of 32 measurements on nonimplanted inserts showed a mean deviation from nominal thickness of −0.021 mm (SD, 0.055 mm; range, −0.152 to +0.076 mm). The manufacturing tolerance was 0.13 mm for all thickness measurements employed for this study.

The RP inserts had a lower ($p = 0.03$) wear rate than the fixed bearing inserts (0.04 versus 0.07 mm/year) (Table 2). The wear rate of the RPs (Fig. 4) did not depend on in vivo duration (Spearmans's rho = 0.176, $p = 0.11$), in contrast to the fixed bearings (Fig. 5), which showed an increasing wear rate with increasing in vivo duration (Spearman's rho = 0.469, $p < 0.001$) (Table 3). The RP bearings showed no difference ($p = 0.72$) in medial and lateral wear, while the fixed bearing inserts showed greater ($p < 0.001$) wear on the medial side (Table 4).

Comparing fixed bearing inserts from the different tray surfaces showed the inserts in polished CoCr trays had better wear performance by several measures: mean depth of backside wear (0.01 versus 0.20 mm, $p < 0.001$), mean backside wear rate (0.006 versus 0.02 mm/year, $p < 0.001$), and volumetric wear rate (10 versus 51 mm^3/year, $p < 0.001$). Separating the fixed bearings by tray type made a noticeable difference in the mobile bearing-fixed bearing comparison: the fixed bearing cohort from the rough Ti trays showed an even larger ($p = 0.001$) difference from RPs (0.09 versus 0.04 mm/year), while the fixed bearing inserts from polished CoCr trays showed a lower ($p = 0.04$) wear rate than the RPs (−0.01 versus 0.04 mm/year). The backside wear rate of the inserts from CoCr trays did not increase with in vivo duration (Spearman's rho = 0.037, $p = 0.83$), whereas the wear rate of inserts from rough Ti trays did (Spearman's rho = 0.494, $p < 0.001$).

The comparison between CR and PS knees did not show a difference in wear rate. In the RP series, the mean wear rate was 0.06 mm/year for CR inserts and 0.03 mm/year for PS inserts ($p = 0.35$). For the fixed bearing series, the mean through-thickness wear rate was 0.07 mm/year for both CR and PS knees ($p = 0.90$).

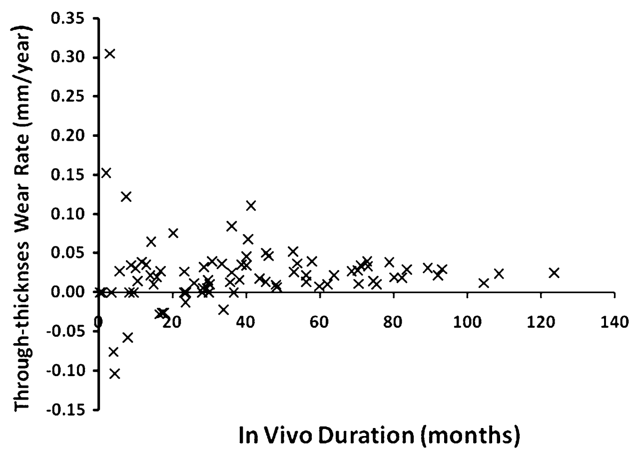

Fig. 4 Through-thickness total wear penetration rate (flexion surface and rotation surface) of Sigma® RP bearings is plotted versus in vivo duration. The wear rate does not depend on in vivo duration.

Table 2. Summary of wear measurements

Device type	Number of retrievals	Backside wear			Through-thickness wear	
		Depth (mm)	Rate (mm/year)	Volumetric rate (mm^3/year)	Depth (mm)	Rate (mm/year)
Sigma® RP						
Curved (CR)	27				0.08 ± 0.08	0.06 ± 0.26
PS	67				0.08 ± 0.10	0.03 ± 0.05
Total RPs	94	NA	NA	NA	0.08 ± 0.09	0.04 ± 0.15
Sigma® fixed bearing Ti trays						
Posterior lipped (CR)	19	0.10 ± 0.11	0.02 ± 0.02	31 ± 38	0.48 ± 0.33	0.08 ± 0.04
Curved (CR)	85	0.24 ± 0.26	0.03 ± 0.03	65 ± 78	0.65 ± 0.61	0.08 ± 0.08
PS	77	0.17 ± 0.27	0.02 ± 0.03	42 ± 53	0.68 ± 0.76	0.10 ± 0.08
Total Ti tray	181	0.20 ± 0.23	0.02 ± 0.03	51 ± 66	0.65 ± 0.66	0.09 ± 0.08
Sigma® fixed bearing CoCr trays						
Posterior lipped (CR)	4	0.02 ± 0.02	0.01 ± 0.01	22 ± 26	−0.003 ± 0.04	−0.008 ± 0.03
Curved (CR)	12	0.03 ± 0.03	0.02 ± 0.02	38 ± 44	−0.02 ± 0.04	−0.02 ± 0.03
PS	21	0.005 ± 0.04	−0.003 ± 0.03	−9 ± 42	0.003 ± 0.04	−0.01 ± 0.05
Total CoCr tray	37	0.01 ± 0.23	0.006 ± 0.02	10 ± 46	−0.005 ± 0.04	−0.01 ± 0.04
Total fixed bearings	218	0.17 ± 0.24	0.02 ± 0.03	44 ± 65	0.52 ± 0.65	0.07 ± 0.08

Values are expressed as mean ± SD; RP = rotating platform; CR = cruciate retaining; PS = posterior stabilized; Ti = titanium; CoCr = cobalt-chrome; NA = not applicable.

Discussion

Many published studies on clinical performance of knees are based on visual assessment of the surfaces of explanted devices [14, 21, 25, 26, 39] and provide important information about in vivo kinematics, impingement, debris, modes of material wear, and other aspects of bearing performance. Measuring actual wear (material loss) from clinical knee retrievals is challenging, in large part because an accurate unworn reference (either gravimetric or dimensional) is usually not known. Our objectives were to contribute quantitative wear measurements from retrieved knee bearings to answer whether RP mobile bearings wear more than fixed bearings in vivo, tibial tray roughness has a measurable impact on backside wear, and there is a difference in wear between CR and PS inserts.

Readers should be aware of the limitations of the study. First, we considered a limited series of retrieved bearings of two designs. Our findings might not apply to other designs. Second, the in vivo duration is longer for the fixed bearing series than for the RP series (179 versus 124 months). In consideration of this difference, wear measurements were presented in terms of both depth of wear and wear rate (normalized for in vivo duration) and conclusions are based only on wear rate. Third, the RP wear measurements and the corresponding through-thickness measurements of fixed bearing inserts represent total wear on both the top and bottom articulating surfaces plus other deformation processes such as creep and pitting. Therefore, the reported wear measurements should be considered a conservatively high value of insert thinning due to abrasive/adhesive wear. We report an estimate of wear volume only for backside wear, for which the area of the worn surface could be accurately measured, and therefore direct comparisons with other studies should be made on the basis of backside-only wear volume.

Our findings indicate the additional articulating surface of the RPs did not increase total wear penetration rate on the inserts compared to fixed bearing inserts. This finding does not support the concern raised by the damaged appearance of the rotation surface of retrieved mobile bearing knees [20, 22, 28] (Table 5). The lack of wear bias to the medial side is consistent with other reports of measured wear of mobile bearings [1, 18, 24] (Table 5) but is

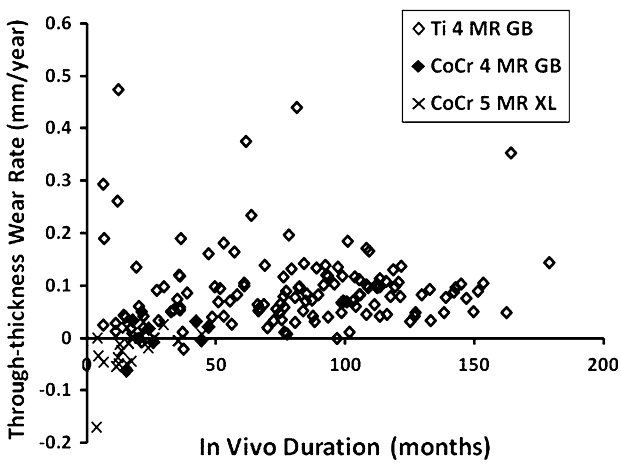

Fig. 5 Through-thickness total wear penetration rate versus in vivo duration is shown for the Sigma® fixed bearing inserts, including those in rough Ti trays with 4-Mrad gamma-irradiated and barrier-packaged material (Ti 4 MR GB) and those in polished CoCr trays with (1) 4-Mrad gamma-irradiated and barrier-packaged material (CoCr 4 MR GB) and (2) 5-Mrad gamma-irradiated and gas plasma-sterilized material (CoCr 5 MR XL). Fixed bearings showed an increasing wear rate with increasing in vivo duration.

Table 4. Summary of t-test results of comparisons of wear rates

Comparison	p value
Fixed bearing Ti tray vs CoCr tray	
Backside wear depth	< 0.001
Backside linear wear rate	< 0.001
Backside volumetric wear rate	< 0.001
RP medial versus lateral wear	0.72
Fixed bearing medial versus lateral wear	< 0.001
RP CR versus PS wear rate	0.35
Fixed bearing CR versus PS wear rate	0.90

Ti = titanium; CoCr = cobalt-chrome; RP = rotating platform; CR = cruciate retaining; PS = posterior stabilized.

Table 3. Summary of statistical comparisons of total through-thickness wear rates

Wear rate	In vivo duration		RP through-thickness wear rate
	Spearman's rho	p value	p value
RP through-thickness wear rate	0.176	0.11	
Fixed bearing through-thickness wear rate	0.469	< 0.001	0.03
Fixed bearing Ti tray wear rate	0.494	< 0.001	0.001
Fixed bearing CoCr tray wear rate	0.037	0.83	0.04

Correlation of wear rates (Column 1) to in vivo duration is shown in Column 2; results of t-test for equality of means between wear rates (Column 1) to RP wear rate are given in Column 3; RP = rotating platform; Ti = titanium; CoCr = cobalt-chrome.

Table 5. Comparison of mobile bearing knee wear assessments from other studies and our study

Study	Bearing type	Implant	Number	In vivo duration (months)*	Assessment method	Wear rate	Notes/Findings
Kop and Swarts [24]	AP mobile	AP Glide®	10	31 (10–51)	CMM, with mathematic reconstruction of unworn surfaces	0.09 mm/year	Same rates for both designs
	RP	LCS®	7	36 (9–70)	Visual rating of damage modes (0–3)	80 mm^3/year (wear volume)	No medial-lateral wear bias
Atwood et al. [1]	RP	LCS®	100	41 (2–170)	Through-thickness measurement	0.09 mm/year	High initial wear rate
					Backside surface only measurement	0.06 mm/year	Lower long-term rate
							No medial-lateral wear bias
							59% had < 2 years' duration
Engh et al. [18]	Mobile	LCS® MB	23	29 (1–102)	Through-thickness measurement (n = 12)	0.047 mm/year	Surface damage did not reflect material lost
					Visual rating of damage modes (0–3)		
Garcia et al. [20]	RP	LCS®	32	30 (0.3–191)	Visual rating of damage modes (0–3)	NA	No medial-lateral difference
	RP	Sigma®	8				Damage increased with duration
							Damage decreased with weight and BMI
							Damage higher in loose knees
Kendrick et al. [23]	Mobile	Oxford® Uni	47	101 (13–200)	Measured bearing thickness	0.07 mm/year	Highest wear with extraarticular impingement
Lu et al. [28]	RP	LCS®	15	121 (48–162)	Visual rating of damage modes (0–3)	NA	Greater damage on top surface of fixed bearings but backside of RPs
							RP damage did not correlate to duration or BMI
							RP top damage correlated to back
Kelly et al. [22]	RP	LCS®	12	36 (10–144)	Visual rating of damage modes (0–3)	NA	Backside damage correlated to duration; top surface does not
		Sigma®	36				Damage does not correlate to BMI
							Damage higher with osteolysis
Current study	RP	Sigma® RP	94	39 (0.4–124)	Through-thickness measurements	0.04 mm/year	No medial wear bias; wear rate does not increase with duration
							No wear difference between CR and PS inserts

* Values are expressed as mean, with range in parentheses; RP = rotating platform; CMM = coordinate measuring machine; CR = cruciate retaining; PS = posterior stabilized; NA = not available.

Table 6. Comparison of fixed bearing knee wear assessments from other studies and our study

Study	Bearing type	Implant	Number	In vivo duration (months)*	Assessment method	Wear rate	Notes/Findings
Benjamin et al. [3]	Fixed	AMK® + PFC®	24	68 (9–132)	Through-thickness measurement	0.35 mm/year	Wear rates decreased with duration
		Synatomic	9		Laser scan for volume	794 mm^3/year (wear volume)	
	Fixed	Synatomic	9		Visual rating of damage pattern (1–6)		
Li et al. [26]	Fixed	AMK®, PFC® Genesis, IB-II	55	1–73	Visual rating of damage modes (0–3) Removal of stamped markings Extrusions into screw holes	87 mg/year	Wear rate estimated for one insert only
Surace et al. [36]	Fixed	MG®	11	64 (4–156)	Visual rating of damage modes (0–3)		Peg heights 0 to 0.317 mm
	Fixed	MG II®	14		Extruded pegs with optical zoom		Pegs indicate most wear posterior, medial
Conditt et al. [12]	Fixed	AMK®	15	91 (36–146)	Linear laser scans of backside, 3D computer reconstruction for volume	138 mm^3/year (wear volume)	Significantly more wear medially
Crowninshield et al. [13]	Fixed	NexGen®	43	33 (2–80)	Visual rating of damage modes (0–3) Profilometry of engraved lettering	0.0041 mm/year	Damage modes: no correlation with duration Backside wear has partial association with duration
Engh et al. [18]	Fixed	AMK®	31	32 (1–141)	Through-thickness measurement (n = 6) Visual rating of damage modes (0–3)	0.047 mm/year	Surface damage did not reflect material lost
Current study	Fixed	Sigma®	218	65 (2.1–179)	Through-thickness and backside measurements Backside wear volume calculated	0.07 mm/year (total) 0.02 mm/year (backside) 44 mm^3/year (wear volume)	Medial wear bias; wear rate increases with duration No wear difference between CR and PS inserts

* Values are expressed as mean, with range in parentheses; CR = cruciate retaining; PS = posterior stabilized.

distinct from our fixed bearing results and those of other reports [12, 36] (Table 6). The RP wear rate of 0.04 mm/year in our study is lower than the 0.09 mm/year reported by Kop and Swarts [24] for relatively small series of both LCS-RP® and AP Glide® inserts and by Atwood et al. [1] for a series of 100 LCS-RP® inserts (Table 5). It is notable, in the study of Atwood et al. [1], the wear rate for in vivo duration of more than 2 years was 1/3 of the series average. In our study, the wear rate of the RPs was not dependent on vivo duration, in clear contrast to the wear rate of the fixed bearing series, which increased with in vivo duration. The wear rate of the fixed bearing inserts was within the range of other published results, which range from 0.0041 mm/year for a study based on erasure of engraved backside lettering [13] to 0.35 mm/year based on through-thickness measurement on a variety of designs [3] (Table 6).

The lower wear rate for the fixed bearing inserts in polished CoCr trays compared with inserts in rough Ti trays confirms findings from in vitro wear studies [4, 19] and retrieval analysis [10]. A further indication of the difference in wear performance is that inserts from Ti trays showed wear rate increasing with in vivo duration, while the inserts from polished CoCr trays did not. Increasing backside wear rate in fixed bearings would be expected due to wear of the insert locking mechanism, a process that has been reported in previous studies of modular fixed bearing knees [11, 31].

Our observations suggest decreasing the roughness of the modular tray has a notable impact on clinical wear. This is demonstrated by the RP inserts, which are free to rotate on a polished tray yet showed lower wear rate than the fixed bearings taken as a whole. It is demonstrated further within the fixed bearing series, which showed a wear rate for inserts from polished CoCr trays lower than both the fixed bearing inserts from rough Ti trays and the RP inserts. The findings suggest limiting insert-to-tray motion alone is not fully effective in reducing wear; optimizing the metal counterface and the relative motion is important. Although there is widely reported evidence of substantial motion of RPs relative to the trays [20, 22, 23, 28], the central post constrains the relative motion to be unidirectional. The backside surface of fixed bearing knees experiences much less extensive motion, but it is multidirectional. Increased wear of polyethylene under conditions of multidirectional motion has been documented by in vitro wear studies [4, 5, 7, 29, 37].

We found no difference in measured wear rate between CR and PS knees. An important design premise of PS knees is that kinematics can be maintained while tibiofemoral surface area is increased and contact stress is accordingly decreased [2, 6, 8, 34]. One hypothesis for the lack of differential performance is that the increased conformity also increases tibiofemoral transmission of torque, which drives rotational motion at the insert-tray interface. Progressive wear of a fixed bearing locking mechanism and a rough tray counterface would be expected to result in increasing backside wear rate, which is what we saw in the fixed bearings from Ti trays. Although the in vivo duration of the CoCr fixed bearings is shorter, that design appears to accommodate backside motion with less insert wear than with the rough Ti counterface.

In summary, we found the wear rate of RP inserts was less than that of fixed bearing inserts, which is in contrast to the indications from retrieval studies based on surface damage assessment. The wear rate of fixed bearing inserts in polished CoCr trays was less than their counterparts in rough Ti trays and was less than the RP inserts. The wear rate of PS and CR inserts was not different. Our findings indicate a polished tray counterface reduces insert wear and the wear rate of inserts against a polished CoCr tray does not appear to increase over time.

Acknowledgments The authors thank the surgeons who have collaborated with our institutions by sending retrieved devices for analysis. We also thank DePuy Orthopaedics, Inc, for providing the design and manufacturing data for the implants studied in this investigation, without which this type of clinical retrieval analysis is not possible.

References

1. Atwood SA, Currier JH, Mayor MB, Collier JP, Van Citters DW, Kennedy FE. Clinical wear measurement on low contact stress rotating platform knee bearings. *J Arthroplasty*. 2008;23:431–440.
2. Bartel DL, Rawlinson JJ, Burstein AH, Ranawat CS, Flynn WF. Stresses in polyethylene components of contemporary total knee replacements. *Clin Orthop Relat Res*. 1995;317:76–82.
3. Benjamin J, Szivek J, Dersam G, Persselin S, Johnson R. Linear and volumetric wear of tibial inserts in posterior cruciate-retaining knee arthroplasties. *Clin Orthop Relat Res*. 2001;392:131–138.
4. Billi F, Sangiorgio SN, Aust S, Ebramzadeh E. Material and surface factors influencing backside fretting wear in total knee replacement tibial components. *J Biomech*. 2010;43:1310–1315.
5. Bragdon CR, O'Connor DO, Lowenstein JD, Jasty M, Syniuta WD. The importance of multidirectional motion on the wear of polyethylene. *Proc Inst Mech Eng H*. 1996;210:157–165.
6. Buechel FF. Mobile-bearing knee arthroplasty: rotation is our salvation! *J Arthroplasty*. 2004;19:27–30.
7. Burroughs BR, Blanchet TA. Factors affecting the wear of irradiated UHMWPE. *Tribol Trans*. 2001;44:215–223.
8. Callagan JJ, Liu SS. Posterior cruciate ligament-substituting total knee arthroplasty. In: Scott WN, ed. *Surgery of the Knee*. New York, NY: Elsevier; 2006:1531–1557.
9. Cheng CK, Huang CH, Liau JJ, Huang CH. The influence of surgical malalignment on the contact pressures of fixed and mobile bearing knee prostheses—a biomechanical study. *Clin Biomech (Bristol, Avon)*. 2003;18:231–236.
10. Collier MB, Engh CA, McAuley JP, Ginn SD, Engh GA. Osteolysis after total knee arthroplasty: influence of tibial baseplate surface finish and sterilization of polyethylene insert—findings at five to ten years postoperatively. *J Bone Joint Surg Am*. 2005;87:2702–2708.

11. Conditt MA, Stein JA, Noble PC. Factors affecting the severity of backside wear of modular tibial inserts. *J Bone Joint Surg Am*. 2004;86:305–311.
12. Conditt MA, Thompson MT, Usrey MM, Ismaily SK, Noble PC. Backside wear of polyethylene tibial inserts: mechanism and magnitude of material loss. *J Bone Joint Surg Am*. 2005;87:326–331.
13. Crowninshield RD, Wimmer MA, Jacobs JJ, Rosenberg AG. Clinical performance of contemporary tibial polyethylene components. *J Arthroplasty*. 2006;21:754–761.
14. Cuckler JM, Lemons J, Tamarapalli JR, Beck P. Polyethylene damage on the nonarticular surface of modular total knee prostheses. *Clin Orthop Relat Res*. 2003;410:248–253.
15. Dennis DA, Komistek RD. Mobile-bearing total knee arthroplasty: design factors in minimizing wear. *Clin Orthop Relat Res*. 2006; 452:70–77.
16. D'Lima DD, Trice M, Urquhart AG, Colwell CW. Tibiofemoral conformity and kinematics of rotating-bearing knee prostheses. *Clin Orthop Relat Res*. 2001;386:235–242.
17. Engh GA, Lounici S, Rao AR, Collier MB. In vivo deterioration of tibial baseplate locking mechanisms in contemporary modular total knee components. *J Bone Joint Surg Am*. 2001;83:1660–1665.
18. Engh GA, Zimmerman RL, Parks NL, Engh CA. Analysis of wear in retrieved mobile and fixed bearing knee inserts. *J Arthroplasty*. 2009;24:28–32.
19. Fisher J, McEwen H, Tipper J, Jennings L, Farrar R, Stone M, Ingham E. Wear-simulation analysis of rotating-platform mobile-bearing knees. *Orthopedics*. 2006;29:S36–S41.
20. Garcia RM, Kraay MJ, Messerschmitt PJ, Goldberg VM, Rimnac CM. Analysis of retrieved ultra-high-molecular-weight polyethylene tibial components from rotating-platform total knee arthroplasty. *J Arthroplasty*. 2009;24:131–138.
21. Hood RW, Wright TM, Burstein AH. Retrieval analysis of total knee prostheses: a method and its application to 48 total condylar prostheses. *J Biomed Mater Res*. 1983;17:829–842.
22. Kelly NH, Fu RH, Wright TM, Padgett DE. Wear damage in mobile-bearing TKA is as severe as that in fixed-bearing TKA. *Clin Orthop Relat Res*. 2011;469:123–130.
23. Kendrick BJ, Longino D, Pandit H, Svard U, Gill HS, Dodd CA, Murray DW, Price AJ. Polyethylene wear in Oxford unicompartmental knee replacement: a retrieval study of 47 bearings. *J Bone Joint Surg Br*. 2010;92:367–373.
24. Kop AM, Swarts E. Quantification of polyethylene degradation in mobile bearing knees—a retrieval analysis of the anterior-posterior-glide (APG) and rotating platform (RP) low contact stress (LCS) knee. *Acta Orthop*. 2007;78:364–370.
25. Landy MM, Walker PS. Wear of ultra-high-molecular-weight polyethylene components of 90 retrieved knee prostheses. *J Arthroplasty*. 1988;3:S73–S85.
26. Li S, Scuderi G, Furman BA, Bhattacharyya S, Schmieg JJ, Insall JN. Assessment of backside wear from the analysis of 55 retrieved tibial inserts. *Clin Orthop Relat Res*. 2002;404:75–82.
27. Lonner JH, Siliski JM, Scott RD. Prodromes of failure in total knee arthroplasty. *J Arthroplasty*. 1999;14:488–492.
28. Lu YC, Huang CH, Chang TK, Ho FY, Cheng CK, Huang CH. Wear-pattern analysis in retrieved tibial inserts of mobile-bearing and fixed-bearing total knee prostheses. *J Bone Joint Surg Br*. 2010;92:500–507.
29. Muratoglu OK, Bragdon CR, O'Connor DO, Jasty M, Harris WH, Gul R, McGarry F. Unified wear model for highly crosslinked ultra-high molecular weight polyethylenes (UHMWPE). *Biomaterials*. 1999;20:1463–1470.
30. Muratoglu OK, Ruberti J, Melotti S, Spiegelberg SH, Greenbaum ES, Harris WH. Optical analysis of surface changes on early retrievals of highly cross-linked and conventional polyethylene tibial inserts. *J Arthroplasty*. 2003;18:42–47.
31. Parks NL, Engh GA, Topoleski LD, Emperado J. The Coventry Award. Modular tibial insert micromotion: a concern with contemporary knee implants. *Clin Orthop Relat Res*. 1998;356:10–15.
32. Rao AR, Engh GA, Collier MB, Lounici S. Tibial interface wear in retrieved total knee components and correlations with modular insert motion. *J Bone Joint Surg Am*. 2002;84:1849–1855.
33. Schmalzried TP, Jasty M, Rosenberg A, Harris WH. Polyethylene wear debris and tissue-reactions in knee as compared to hip-replacement prostheses. *J Appl Biomater*. 1994;5:185–190.
34. Scuderi GR, Clarke HD. Cemented posterior stabilized total knee arthroplasty. *J Arthroplasty*. 2004;19:17–21.
35. Sharkey PF, Hozack WJ, Rothman RH, Shastri S, Jacoby SM. Insall Award paper. Why are total knee arthroplasties failing today? *Clin Orthop Relat Res*. 2002;404:7–13.
36. Surace MF, Berzins A, Urban RM, Jacobs JJ, Berger RA, Natarajan RN, Andriacchi TP, Galante JO. Coventry Award paper. Backsurface wear and deformation in polyethylene tibial inserts retrieved postmortem. *Clin Orthop Relat Res*. 2002;404:14–23.
37. Wang A. A unified theory of wear for ultra-high molecular weight polyethylene in multi-directional sliding. *Wear*. 2001;248:38–47.
38. Wasielewski RC, Parks N, Williams I, Surprenant H, Collier JP, Engh G. Tibial insert undersurface as a contributing source of polyethylene wear debris. *Clin Orthop Relat Res*. 1997;345:53–59.
39. Wright TM, Rimnac CM, Stulberg SD, Mintz L, Tsao AK, Klein RW, McCrae C. Wear of polyethylene in total joint replacements: observations from retrieved PCA knee implants. *Clin Orthop Relat Res*. 1992;276:126–134.