Chapter 8
Wear Studies of the LCS

8.1 Wear-analysis of Mobile Bearing Knee*

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1 Introduction

Improvements in total knee replacement (TKR) designs, materials and sterilization techniques during the past decade have led to improved clinical performance of these joints by reducing the prevalence of delamination and structural fatigue of the ultra high molecular weight polyethylene (UHMWPE) bearings. However, in the longer term, concern remains regarding the surface wear of total knee components as the generation and accumulation of micrometre and submicrometer size wear particles has been observed in tissues surrounding knee prostheses that were revised for infection in the early years of implantation [5]. This may lead to osteolysis and long-term failure mechanisms similar to those found in total hip replacements [6]. The generation of UHMWPE wear debris from articulating surfaces in knee prostheses is controlled by a number of factors. These include damage or scratching to the femoral and tibial counterfaces, kinematic input conditions (in particular the amount of internal-external rotation) and the design of the knee components.

Current TKR devices can be subdivided into two groups based on different fundamental design principles: fixed bearing knees, where the UHMWPE insert snap or press fits into the tibial tray, and mobile bearing designs which facilitate movement of the insert relative to the tray. As the polymer insert in fixed bearing knees is constrained in the tibial tray, rotation of the knee occurs at the femoral-insert articulation. Anterior-posterior (AP) translation and internal-external (IE) rotation also occur at this interface. Therefore, a multidirectional wear path results. However, in some mobile bearing knee designs, it is possible to decouple the bearing motions, by allowing rotation at the tray-insert counterface, hence reducing the degree of rotation at the femoral-insert articulation.

We hypothesize that the rotating platform mobile bearing TKR design translates complex knee kinematics into more linear motions at the superior and inferior surfaces of the polyethylene bearing, thus reducing polyethylene wear. This chapter reviews recent studies which have compared the wear of rotating platform mobile bearing knees with that of fixed bearing components under different kinematic and counterface conditions. The influences of mobile bearing and fixed bearing knee designs on surface wear and osteolytic potential are discussed.

2 Materials

The wear of fixed bearing and rotating platform mobile bearing TKRs was compared using the Leeds ProSim six-station force/displacement controlled knee simulator and also using an AMTI six-station displacement controlled simulator [10, 12]. Size 3, Press Fit Condylar (PFC) Sigma fixed bearing TKR components were tested (DePuy). Curved tibial inserts (GUR1020 UHMWPE) of 10 mm thickness were assembled by snap fit into titanium alloy (Ti-6Al-4 V) tibial trays. The bearings articulated with posterior cruciate retaining, right, Co-Cr-Mo alloy femoral components. Low Contact Stress (LCS) Rotating Platform (RP) mobile bearing TKR were also investigated (DePuy). On the Leeds simulators, Standard size, cruciate sacrificing, right, Co-Cr-Mo alloy femoral components articulated with LCS Universal, Standard, 10 mm thick inserts which were machined from GUR1020 UHMWPE. The bearings freely rotated within size 3, LCS Universal, Co-Cr-Mo alloy tibial trays. Similar LCS systems were tested on the AMTI simulator but consisted of Std+ size components with Deep Dish Rotating Platform inserts of 10 mm thickness.

Six (n=6) TKR of a single design were tested under each set of conditions on the Leeds simulator whereas

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three (n=3) replicate mobile bearing TKR or six (n=6) replicate fixed bearing components were tested simultaneously in each AMTI simulator study. All tibial inserts were packaged in foil pouches prior to sterilisation by a nominal dose of 4.0 MRad gamma irradiation in a vacuum (1020 GVF).

3 Methods

3.1 Standard Conditions

Femoral axial loading (maximum 2600 N) and extension-flexion (0°–58°) input profiles were adopted from the ISO 14243-1 [7] draft standard for simulator studies at both test centers (Fig. 1).

For testing using the Leeds simulator, tibial rotation was displacement controlled with internal-external rotation of ±5° based on the natural knee kinematics described by Lafortune et al. [9]. AP sliding translation of the tibial trays was displacement controlled (0–10 mm) for the fixed bearing knees according to natural knee profiles [9]. However, the ISO 14243-1 [7] AP force profile (–262 N to 110 N) was input to the mobile bearing knees as the rotating platform design restricts AP motion. These input profiles are shown in Fig. 2.

The compressive load applied to each knee was offset 5 mm medially from the tibial axis, as recommended in the ISO 14243 [7] standard for a knee of the dimensions used in this study. The simulator was run at a frequency of 1 Hz and the lubricant used for testing was 25 % (v/v) newborn calf serum (Harlan Sera-Lab, Loughborough, UK) with 0.1 % (m/v) sodium azide solution in sterile water. The serum solution in each station was replaced at intervals of approximately 330,000 cycles.

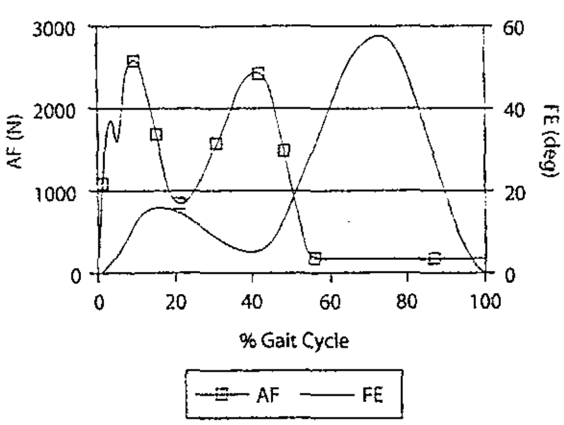


Fig. 1. Knee simulator input profiles for axial force (AF) and flexion-extension (FE)

Motion profiles for the AMTI simulator testing were adopted from the proposed standard for displacement control (ISO 14243-3 [7]). This resulted in anterior-posterior sliding translation of 0–5.2 mm and internal-external rotation of +2°/–6° (Fig. 3).

The applied load was offset so that 60 % and 40 % of the compressive force was applied to the medial and lateral condyles, respectively, and the simulator was cycled at a frequency of 2 Hz. The test lubricant was a solution of 90 % (v/v) bovine serum (HyClone, Logan, Utah, USA) with 0.2 % (w/v) sodium azide in 20 mM EDTA and was filtered through a 0.2 μm filter prior to use. This lubricant was replaced at intervals of one million cycles. All kinematic input profiles used in the Leeds and AMTI simulator testing are summarized in Table 1.

Components were tested in the knee simulators for up to five million cycles, which is equivalent to approximately five years service in vivo. Gravimetric measure-

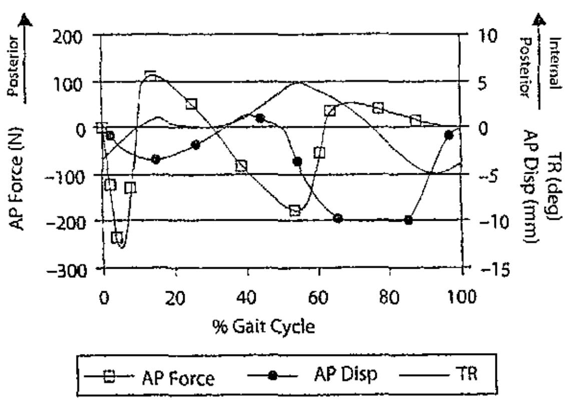


Fig. 2. Leeds knee simulator input profiles for anterior-posterior (AP) force, AP sliding displacement and internal-external tibial rotation (TR)

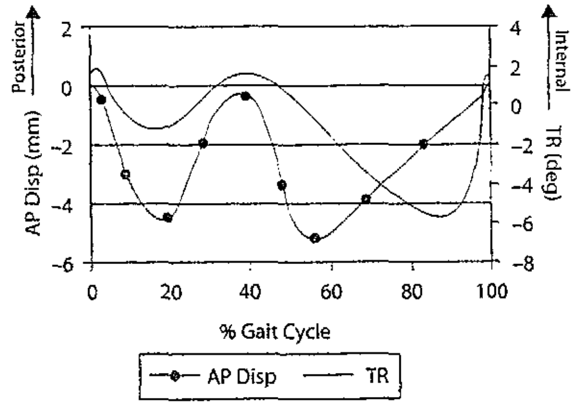


Fig. 3. AMTI knee simulator input profiles for anterior-posterior (AP) sliding displacement and internal-external tibial rotation (TR)

Table 1. Inputs for standard and reduced kinematics testing on the Leeds and AMTI knee simulators

Kinematics	TKR Design	Maximum Axial Force (N)	Flexion-Extension (°)	Anterior-Posterior Translation	Internal-External Rotation (°)
Leeds Standard	PFC Sigma	2600	0–58	0–10 mm	±5
	LCS RP	2600	0–58	–262 N to 110 N	±5
Leeds Reduced	PFC Sigma	2600	0–58	0–5 mm	±2.5
AMTI Standard	PFC Sigma	2600	0–58	0–5.2 mm	+2/–6
	LCS RP	2600	0–58	0–5.2 mm	+2/–6
AMTI Reduced	PFC Sigma	2000	0–58	0–2.6 mm	0/–3

ments of the tibial inserts were obtained before testing and at half million or million cycle intervals. Unloaded soak controls in serum solution were used to monitor moisture uptake. Volumetric wear of the bearings was calculated from the weight loss of the inserts during testing and using density of 0.934 mg/mm^3 for the 1020 GVF polyethylene. The wear rate under each set of conditions was defined as the slope of the linear regression line for cumulative volumetric wear versus the number of cycles completed in the test. Digital images of the wear scars on the superior surfaces of the UHMWPE bearings were obtained after completion of testing. The area of each wear scar from the Leeds simulator was quantified and then expressed as a percentage of the intended articulating area. In addition, femoral and tibial tray surface damage was analyzed using a Form Talysurf stylus profilometer.

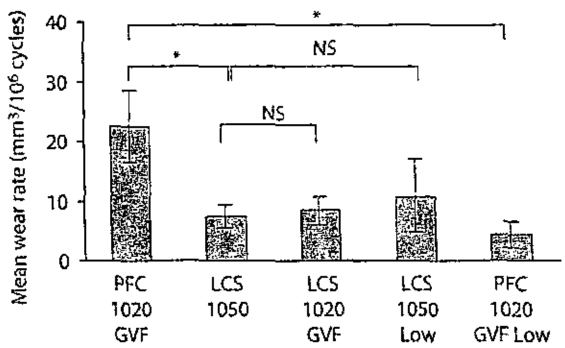


Fig. 4. Mean wear rates with 95% confidence limits for PFC Sigma and LCS Rotating Platform TKR components with the Leeds simulator using standard conditions (PFC 1020 GVF, LCS 1020 GVF) and reduced kinematics (PFC 1020 GVF Low). Note: * significant difference ($p<0.05$)

3.2 Kinematics

The effect of kinematic input conditions on UHMWPE wear in fixed bearing TKR was examined at both test centers using the PFC Sigma knee design. Six PFC Sigma knees were tested under "low" kinematic conditions on a Leeds knee simulator for three million cycles. During this testing, the internal-external rotation and anterior-posterior sliding translation motions were reduced to half the values used for the standard condition studies, that is ±2.5° and 0–5 mm, respectively.

Reduced kinematic testing was also completed on the AMTI knee simulator. Six PFC Sigma TKR were subjected to eight million cycles with reduced inputs for axial force (maximum 2000 N), AP sliding displacement (0–2.6 mm) and internal-external rotation (0/–3°).

3.3 Femoral Counterface Damage

The influence of femoral counterface damage on TKR wear was investigated using the Leeds simulator. One scratch (mean Rp = 1.69±0.50 µm, mean Rv = 2.96±0.51 µm) was inscribed on the center of each condyle of the PFC Sigma femoral components parallel to the flexion-extension direction using a conical diamond stylus (50 µm diameter). Similar scratches (mean Rp = 1.73±0.56 µm, mean Rv = 2.72±0.37 µm) were positioned on the LCS RP femoral components. Each set of knee components was tested for one million cycles while subjected to the standard kinematic input conditions.

4 Results

4.1 Standard Conditions

The PFC Sigma fixed bearing knees exhibited a mean wear rate with 95% confidence limits of 22.75±5.95 cubic millimeters per million cycles (mm^3/MC) when subjected to high rotation kinematics in the Leeds simulator testing (Fig. 4).

In contrast, a mean wear rate of 10.85±2.39 mm^3/MC was observed for the LCS Rotating Platform mobile bearing components. This twofold reduction in wear of the rotating platform mobile bearing knees in com-

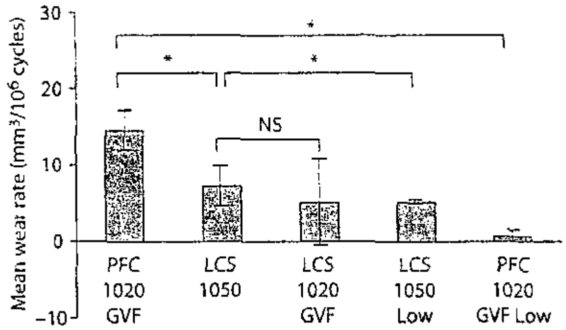
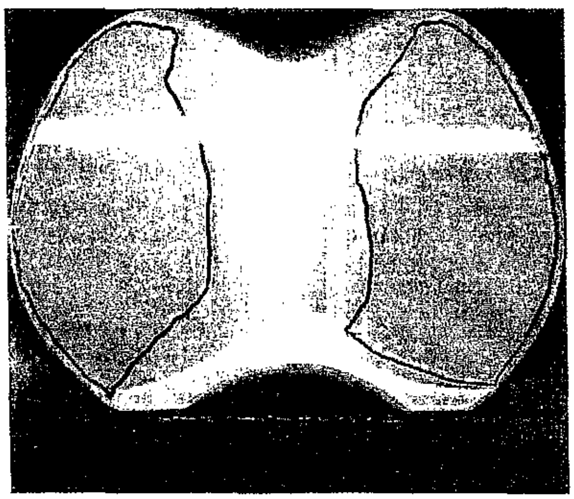


Fig. 5. Mean wear rates with 95% confidence limits for PFC Sigma and LCS Rotating Platform TKR components with the AMTI simulator using standard conditions (PFC 1020 GVF, LCS 1020 GVF) and reduced kinematics (PFC 1020 GVF Low). Note: * significant difference ($p<0.05$)



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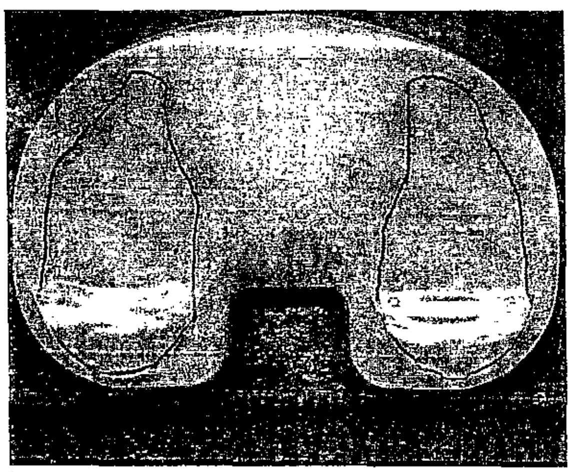

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Fig. 6a,b. Example wear scars for a LCS Rotating Platform mobile bearing; and b PFC Sigma fixed bearing TKR after standard testing in the Leeds simulator. Note: Anterior towards top and medial towards left of images

parison to the fixed bearing knees was highly significant ($p<0.01$). Displacement-controlled testing on the AMTI simulator similarly revealed a highly significant ($p<0.01$) two-fold reduction in wear for the mobile bearing knees with mean wear rates of 14.57±2.63 mm³/MC and 5.19±5.61 mm³/MC observed for the PFC Sigma and LCS RP inserts, respectively (Fig. 5).

The large error bars reported for the AMTI simulator test with LCS RP components resulted from the small sample size included in the study. Differences in the absolute wear rates obtained at each center may be attributed to differences in test conditions, such as serum concentrations and cycle frequencies.

The mean wear scar areas with 95% confidence limits on the femoral articulating surfaces of the Leeds PFC Sigma and LCS RP tibial inserts, expressed as a percentage of the total articulating area, were 48±3% and 70±7%, respectively (Fig. 6).

This difference in wear area was highly significant ($p<0.01$) and confirms the low contact stress design principle of the LCS Rotating Platform TKR.

Deep scratches with no obvious lips were observed on the Leeds PFC Sigma femoral components parallel to the flexion-extension motion. Significant fretting wear was observed on the superior surfaces of the PFC Sigma tibial trays in the direction of tibial rotation and was located primarily towards the rim on both the medial and the lateral condyles, indicating a lack of wear resistance of the titanium alloy surface. Microscopic examination revealed large pits where particles had been plucked out of the titanium alloy surface. It is postulated that these particles were removed from the tray-insert articulation by the entraining motion of the lubricant and subsequently caused the scratching observed on the femoral components.

Scratches were observed on the LCS femoral components in a similar direction to those present on the PFC Sigma components but these tended to be shallower. The LCS tibial trays exhibited severe scratching in the direction of tibial rotation with the counterface damage worsening towards the medial and lateral edges of the trays. Similar scratching and wear patterns were observed on the PFC Sigma and LCS RP components tested using the AMTI simulator.

4.2 Kinematics

When subjected to low kinematic inputs on a Leeds simulator, the wear rate exhibited by the PFC Sigma components was only 4.36±2.12 mm³/MC (see Fig. 4). This five-fold wear reduction, in comparison to the wear observed under high kinematics, was highly significant ($p<0.001$).

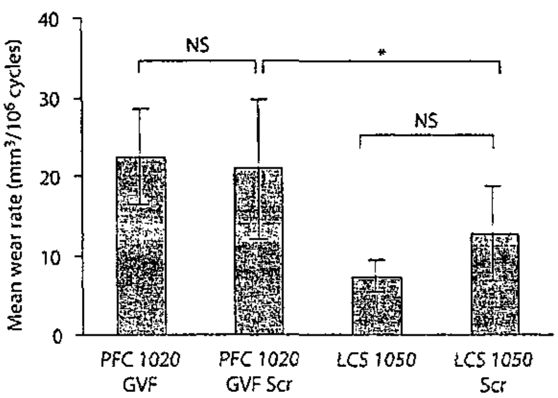

Fig. 7. Mean wear rates with 95% confidence limits for PFC Sigma and LCS Rotating Platform TKR components with the Leeds simulator using standard conditions (PFC 1020 GVF, LCS 1020 GVF) and with femoral scratching (PFC 1020 GVF Scr, LCS 1020 GVF Scr). Note: * significant difference ($p<0.05$), *NS* no significant difference

The AMTI knee simulator testing also revealed a highly significant ($p<0.001$) decrease in UHMWPE wear for the PFC Sigma knees when the AP displacement, IE rotation and axial force inputs were reduced (see Fig. 5).

4.3 Femoral Counterface Damage

No significant increase in UHMWPE wear rate was observed when the PFC Sigma femoral components were intentionally scratched parallel to the direction of flexion-extension and subsequently subjected to high rotation kinematics on the Leeds simulator ($p>0.05$; Fig. 7).

Similarly, the wear rate of the rotating platform bearings did not increase significantly after the femoral components were intentionally scratched ($p>0.05$). However, when each TKR design was articulated against intentionally scratched femoral components, the PFC Sigma knees still exhibited a significantly greater wear rate than the LCS RP components ($p<0.05$).

5 Discussion

5.1 Effect of TKR Design

The LCS Rotating Platform TKR has significantly greater conformity between the polyethylene insert and the femoral component in comparison to the PFC Sigma knee, as evidenced by the larger wear scars on the superior surfaces of the polyethylene bearings. However, despite increased contact areas on both the tibial and femoral counterfaces of the inserts, the LCS RP mobile bearing knees produced a significantly lower mean volumetric wear rate of polyethylene than the PFC Sigma fixed bearing components when subjected to high internal-external rotation kinematic inputs. This trend was observed on the knee simulators at both test centers despite use of different test frequencies and serum lubricant concentrations, thereby revealing that TKR design was the dominant factor affecting UHMWPE wear.

We postulate that the rotating platform mobile bearing design decouples the motions between the femoral-insert and tray-insert articulating surfaces. Most of the rotation occurs at the distal tibial articulating surface of the UHMWPE insert, which is simply a unidirectional rotation motion that is known to produce low wear [11, 15]. Since the majority of the rotation occurs at the distal interface, the proximal femoral articulating interface experiences very low rotation. Therefore, at the femoral-insert articulation the motion is also preferably unidirectional and similarly has a low wear rate. Hence, the unique design of the rotating platform mobile bearing knee translates complex input motions into more unidirectional motions, thus benefiting from a reduced wear rate due to decreased cross shear on the molecularly oriented UHMWPE.

In contrast, rotation of the knee with the PFC Sigma fixed bearing TKR occurs entirely at the femoral-insert articulation. The resulting multidirectional wear path at this interface increases the amount of cross shear on the polyethylene articulating surface and, therefore, produces a greater polymer wear rate when subjected to high rotation kinematic inputs.

5.3 Effect of Kinematics

In vitro wear of fixed bearing TKR components in knee joint simulators is highly dependent on kinematic inputs for AP translation and IE rotation [8]. Using a Leeds ProSim knee simulator, Barnett et al. [2] revealed that a twofold reduction of IE rotation and AP displacement inputs to PFC (DePuy) knees produced a fivefold reduction in UHMWPE wear. This phenomenon was further evidenced, as described in this chapter, by the fivefold reduction in wear of the PFC Sigma fixed bearing components on the Leeds simulator when subjected to the low kinematic inputs and also by the substantial reduction in PFC Sigma wear on the AMTI simulator with reduced kinematic inputs. This has potential consequences for highly active patients.

The greater wear of the PFC Sigma fixed bearing components under high kinematics in comparison to low kinematics may be attributed to the increased cross shear on the polyethylene when subjected to greater internal-external rotation. UHMWPE becomes molecularly oriented in the principal direction of sliding (anterior-posterior), producing a strain hardened effect which increases the wear resistance [13, 15]. Consequently, the polyethylene strain softens along the axis transverse to the sliding motion and exhibits less wear resistance in that direction. Introducing a motion such as internal-external rotation, which produces a friction force in the direction transverse to sliding, increases the polymer wear rate. Therefore, the cross shear, which results from increased rotation when fixed bearing knees are subjected to high kinematic input conditions, accelerates polyethylene wear.

5.3 Effect of Femoral Counterface Damage

Total hip replacement retrieval studies and laboratory tests have revealed that discrete scratches on the metallic counterface, located perpendicular to the principal direction of sliding, can increase UHMWPE wear rates by a factor of two to three [1, 14]. However, in vivo scratches observed on knee retrievals primarily occur on the femoral component in the anterior-posterior direction, which is parallel to the principal sliding direction [4]. Whilst the primary direction of sliding in the knee is anterior-posterior as a result of flexion-extension motion, there is also a degree of multidirectional motion produced by internal-external rotation of the joint. This has the potential to accelerate the wear of UHMWPE in the presence of scratched femoral components. However, in both the fixed bearing and the rotating platform mobile bearing knees tested in this study, no significant increase in UHMWPE wear was observed after deliberate scratching of the femoral components parallel to the principal direction of sliding. This supports the postulate that scratches positioned parallel to the principal direction of motion have less effect on UHMWPE wear than scratches located perpendicular to the direction of sliding. However, a significant reduction in wear was still observed with RP mobile bearing knees in comparison to PFC Sigma fixed bearing TKR when articulated against scratched counterfaces.

6 Conclusions

The potential for long term osteolysis necessitates minimization of the number of particles generated due to TKR surface wear, particularly for implantation in younger, more active patients. Despite increased contact areas on both the tibial and femoral counterfaces and the presence of two articulating surfaces, the LCS Rotating Platform mobile bearing knees produced a significantly lower volumetric wear rate of polyethylene than the PFC Sigma fixed bearing knees when subjected to high kinematic inputs. The unique design of the rotating platform mobile bearing knee translates complex input motions into more unidirectional motions, thus benefiting from a reduced wear rate due to decreased cross shear on molecularly oriented UHMWPE. This tribological advantage of reduced polymer wear in rotating platform TKR has been evidenced in simulator studies completed at two independent test centers with different cycle frequencies and lubricant concentrations. Therefore, patients with higher activity levels may benefit from the implantation of a rotating platform mobile bearing knee.

The wear of fixed bearing TKR decreased significantly when kinematic inputs were reduced, which has implications for highly active patients. Femoral counterface scratching parallel to the principal direction of sliding did not significantly affect UHMWPE wear rates in the PFC Sigma fixed bearing or LCS Rotating Platform mobile bearing knees. However, the significant reduction in wear provided by RP mobile bearing TKR in comparison to fixed bearing knees still remained when articulated against scratched counterfaces.

Thus, the design of TKR chosen for implantation is an important factor that influences UHMWPE surface wear and may affect the long-term success of total knee replacements.

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