Wear of fixed bearing and rotating platform mobile bearing knees subjected to high levels of internal and external tibial rotation

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In order to extend the lifetime of total knee replacements (TKR) *in vivo*, reduction of the volumetric wear rate of ultra high molecular weight polyethylene (UHMWPE) bearings remains an important goal. The volume of wear debris generated in fixed bearing total knee devices increases significantly when subjected to higher levels of internal–external rotation and anterior–posterior displacement. Six PFC Sigma fixed bearing TKR were compared with six LCS rotating platform mobile bearing knees using a physiological knee simulator with high rotation kinematic inputs. The rotating platform polyethylene inserts exhibited a mean wear rate which was one-third of that of the fixed bearing inserts despite having increased femoral contact areas and additional tibial wear surfaces. The rotating platform design decouples knee motions, by allowing unidirectional motion at the tray-insert articulation, which reduces rotation at the femoral-insert counterface. This translation of complex knee motions into more unidirectional motions results in molecular orientation of the UHMWPE and reduced volumetric wear.

Introduction

The generation of ultra high molecular weight polyethylene (UHMWPE) wear particles and the resulting osteolysis is a cause of long-term loosening of total knee replacement (TKR) joints [1]. To extend the lifetime of total knee implants *in vivo*, reduction of the volumetric wear rate of UHMWPE bearings remains an important goal. Current TKR devices can be subdivided into two groups: 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 cannot move relative to the tibial tray, rotation of the knee occurs at the femoral-insert articulation. Anterior–posterior (AP) translation and flexion–extension (FE) also occur at this interface. Therefore, a multidirectional wear path results. *In vitro* wear of fixed bearing TKR components in knee simulators is highly dependent on kinematic inputs for internal–external (IE) rotation and AP translation [2]. Recently, a two-fold reduction of IE rotation and AP displacement produced a five-fold decrease in wear for a series of fixed bearing knees [3]. Patients who have higher activity levels may produce larger volumes of polyethylene wear debris with fixed bearing TKR.

In some mobile bearing knee designs it is possible to decouple the bearing motions, by allowing rotation at the tray-insert counterface, hence reducing rotation at the femoral-insert counterface. We hypothesize that the rotating platform mobile bearing knee design decouples these motions, by facilitating linear rotation at the tray-insert articulation, and reduces the degree of multi-directional motion at the femoral-insert articulation, thus reducing wear of the UHMWPE bearing. The purpose of this study was to compare the wear of rotating platform mobile bearing knees with that of fixed bearing components when subjected to high IE rotation kinematic inputs in a physiological knee simulator.

Materials and methods

Six ($n = 6$) size 3, right, PFC Sigma fixed bearing TKR components were tested (DePuy, Leeds, UK). Curved tibial inserts (GUR1020 UHMWPE) of 10 mm thickness were assembled by snap fit into titanium alloy (Ti-6Al-4V) tibial trays. The bearings articulated with posterior cruciate retaining, Co–Cr–Mo alloy femoral components.

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Six ($n = 6$) right, LCS Rotating Platform (RP) mobile bearing TKR were also investigated (DePuy, Leeds, UK). Standard, cruciate sacrificing, Co–Cr–Mo alloy femoral components articulated with LCS Universal, standard, 10 mm thick inserts (GUR1050 UHMWPE). The bearings freely rotated within size 3, LCS Universal, Co–Cr–Mo alloy tibial trays. The PFC components were packaged in foil pouches prior to sterilization by 2.5–4.0 MRad of gamma irradiation in a vacuum (GVF) whereas gas plasma (GP) methods were utilized for sterilization of the LCS components.

Testing was completed using a six-station force/displacement controlled knee simulator (ProSim, Manchester, UK) which has been described previously [4]. Femoral axial loading (maximum 2600 N) and extension–flexion (0°–58°) input profiles were adopted from the draft standard ISO/DIS 14243-1. Tibial rotation was displacement controlled with internal–external rotation of $\pm 5°$ based on the natural knee kinematics described by Lafortune *et al*. [5]. This rotation profile, which had greater amplitude than that recommended in the proposed ISO standard for displacement control (ISO/WD 14243-3), was employed so that kinematic conditions were representative of patients with high activity levels. AP translation of the tibial trays was displacement controlled (0–10 mm) for the fixed bearing knees according to natural knee profiles [5]. The ISO/DIS 14243-1 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. 1. Limits of 300 N and 8 Nm for AP force and IE rotation torque were applied respectively when these motions were operated using displacement control. The load applied to each knee was offset 5 mm medially from the tibial axis, as recommended in the draft ISO standard for a knee of the dimensions used in this study.

The simulator was run at 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 deionized water. The serum in each station was replaced after every 330 000 cycles. Knee components were tested in the simulator for up to six million cycles, which is equivalent to approximately six years service *in vivo*.

Prior to testing, the polyethylene inserts were soaked in deionized water for a minimum of three weeks. Gravimetric measurements of the tibial inserts were obtained before testing and after every million cycles completed in the knee simulator, using a Mettler AT201 (Leicester, UK) digital microbalance with resolution 0.01 mg and accuracy ± 0.015 mg. Unloaded soak controls were used to monitor moisture uptake and weighing conditions. Volumetric wear of the bearings was calculated from the weight loss of the inserts during testing and using densities of 0.934 and 0.932 mg/mm^3 for the GUR1020 GVF (PFC) and GUR1050 GP (LCS) bearings, respectively. Digital images of the wear scars on the superior surfaces of the bearings were obtained at the end of testing by manually tracing the outline of the scar and capturing the image using a Seiko Epson GT-7000 scanner (Nagano, Japan). The area of each wear scar was quantified (Image-Pro Plus 3.0, Media

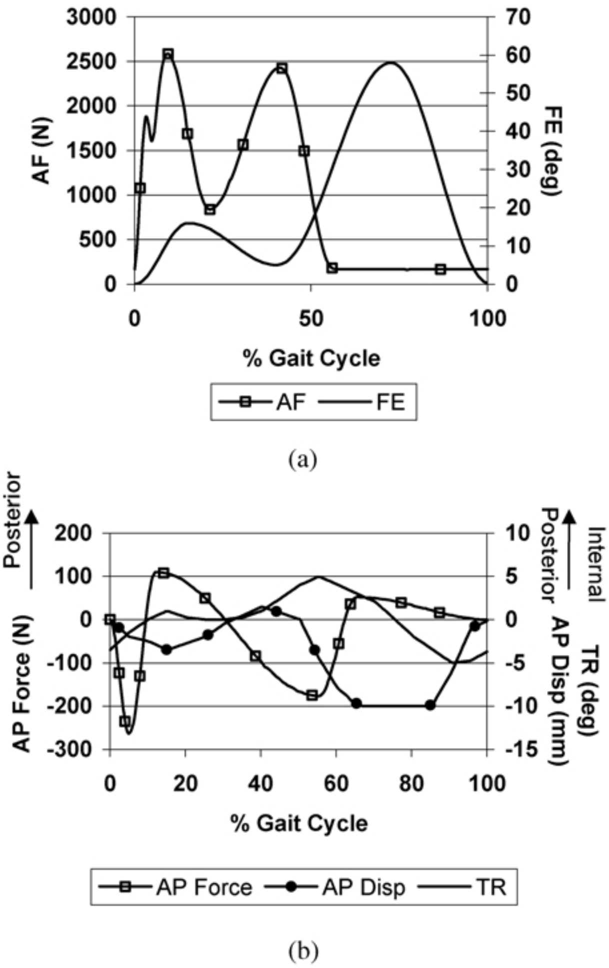


Figure 1 Knee simulator input profiles for (a) axial force (AF) and flexion–extension (FE); and (b) anterior–posterior (AP) force, AP displacement and IE tibial rotation (TR).

Cybernetics, MD, USA) and then expressed as a percentage of the total articulating area.

At the completion of testing, femoral and tibial tray surface damage was analyzed using a Form Talysurf (Taylor Hobson, Leicester, UK) stylus profilometer (stylus radius = 2.5 μm). A custom jig was manufactured to obtain traces of length 10 mm across each condyle of the femoral components at desired angles of flexion. Traces of length 10–12 mm were obtained at specific locations on the PFC and LCS trays. The mean average surface roughness (Ra) was calculated for the PFC trays by filtering along the length of each trace (ISO filter, 0.8 mm cutoff). Scratching on the LCS femorals, LCS trays and PFC femorals was quantified, in terms of maximum/minimum depth of the trace profile above/below the mean profile height within the sample length (Rp/Rv), using unfiltered traces.

Results

The PFC fixed bearing knees exhibited a mean wear rate with 95% confidence limits of $22.12 \pm 6.02\ mm^3$/million cycles. In contrast, a mean wear rate of only $7.34 \pm 1.81\ mm^3$/million cycles was observed for the LCS mobile bearing components (Fig. 2). Therefore, the fixed bearing knees exhibited a mean wear rate three times greater than that of the rotating platform mobile bearing knees and this difference was highly significant

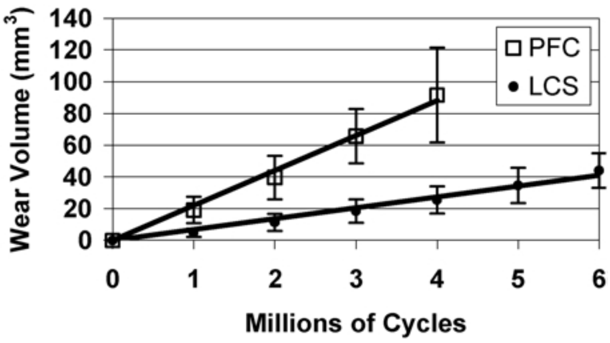


Figure 2 Mean cumulative volumetric wear with 95% confidence limits for PFC Sigma and LCS Rotating Platform TKRs.

($p < 0.001$). The mean wear scar areas with 95% confidence limits on the femoral articulating surfaces of the PFC and LCS tibial inserts, expressed as a percentage of the total articulating area, were $35 \pm 6\%$ and $70 \pm 7\%$, respectively (Fig. 3). Therefore, the mean wear area on the rotating platform mobile bearing knees was two times greater than that observed on the fixed bearing knees. The difference in area was highly significant ($p < 0.001$) and confirms the low contact stress design principle.

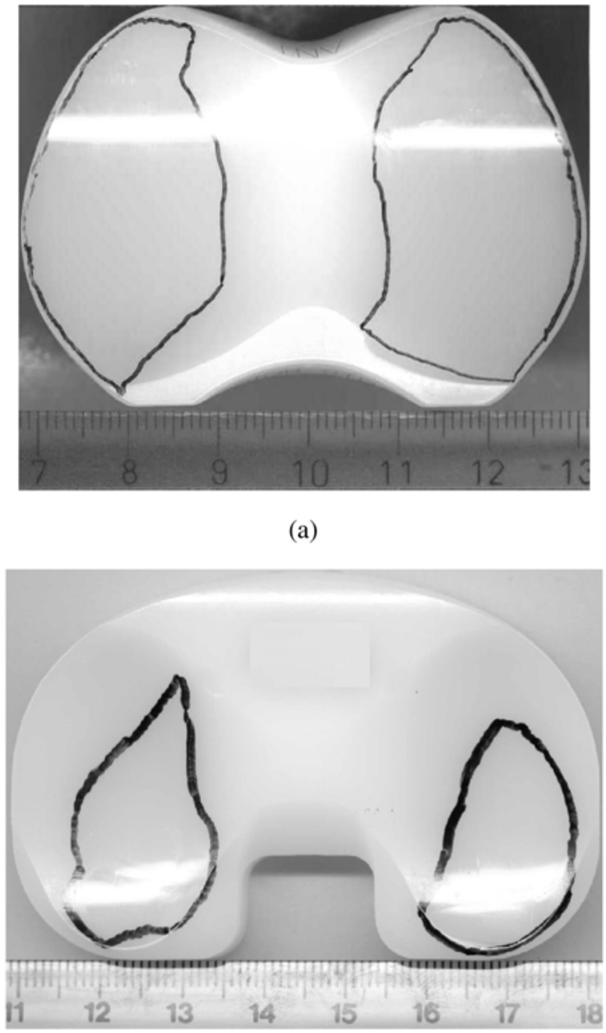
Deep scratches ($Rv \leq 10.8\,\mu m$) with no obvious lips ($Rp \leq 0.3\,\mu m$) were observed on the PFC femoral components parallel to the flexion–extension motion. Significant fretting was observed on the superior surfaces of the PFC tibial trays in the direction of tibial rotation and was located primarily towards the rim on both the medial and the lateral condyles. 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 deep scratching observed on the femoral components. The mean average surface roughness (Ra) of the tibial trays tended to decrease after testing in the knee simulator. Hence, smoothing of the trays occurred, indicating micromotion between the polymer bearing and the tibial tray.

Scratches were observed on the LCS femorals in a similar direction to those present on the PFC components but were more shallow ($Rv \leq 3.95\,\mu m$, $Rp \leq 0.1\,\mu m$). The LCS tibial trays exhibited severe scratching ($Rv \leq 8.00\,\mu m$, $Rp \leq 0.12\,\mu m$) in the direction of tibial rotation with the counterface damage worsening towards the medial and lateral edges of the trays.

Discussion

The LCS rotating platform knee design has significantly greater conformity between the polyethylene insert and the femoral component in comparison to the PFC knee design. The larger wear scars produced on the LCS bearings were evidence of this. However, the increased femoral wear areas and the additional tibial wear surfaces did not lead to greater wear in the mobile bearing knees.

Wear of polyethylene can be reduced by decreasing the amount of rotation to which the material is subjected, that is by decreasing the multidirectionality of the motion [6]. The rotating platform mobile bearing knee design translates knee rotation into unidirectional motion at



(a)

(b)

Figure 3 Example wear scars for (a) LCS Rotating Platform mobile bearing; and (b) PFC fixed bearing knee inserts. *Note:* Anterior towards top and medial towards left of images.

the tibial tray-insert articulation with reduced rotation occurring at the femoral-insert interface. Therefore, the more unidirectional motion at the femoral-insert articulation decreases the amount of polyethylene wear generated. The fixed bearing PFC components, which are subject to greater multidirectional motion, exhibited significantly increased wear in the simulator in comparison to the mobile bearing knees.

UHMWPE experiences strain hardening under uniaxial stretching, as the lamellar crystals can rotate and realign themselves along the direction of deformation, thus providing greater wear resistance for unidirectional sliding [7]. This molecular orientation induces anisotropy and weakens the inter–fiber strength in the transverse direction (strain softening). Hence, wear resistance of the polymer is reduced when subjected to multidirectional sliding and shear [8]. In the knee joint, the principle direction of strain hardening at the femoral-insert counterface is parallel to the flexion–extension axis [8]. By decoupling complex motions of the knee into unidirectional motions at each counterface, the rotating platform TKR benefits from strain hardening in the principle directions of motion at each articulating surface and, therefore, experiences reduced wear.

Under force control, the high conformity of the LCS rotating platform knee resulted in AP translation of less than 4 mm, that is less than half that experienced by the PFC components. It should be noted, therefore, that the smaller AP displacement may have contributed further to the reduced wear observed in the mobile bearing knees. In addition, the low contact stress, low rotational constraint forces, different UHMWPE base resin and alternate method of sterilization may have influenced the wear properties of the LCS knee design.

Conclusions

Despite increased contact areas on both the tibial and femoral counterfaces, the LCS rotating platform mobile bearing knees produced a significantly lower volumetric wear rate of polyethylene than the PFC fixed bearing components when subjected to high IE tibial rotation 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 molecular orientation of the UHMWPE.

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