Wear-pattern analysis in retrieved tibial inserts of mobile-bearing and fixed-bearing total knee prostheses


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Components from 73 failed knee replacements (TKRs) consisting of rotating-platform, mobile-bearing and fixed-bearing implants were examined to assess the patterns of wear. The patterns were divided into low-grade (burnishing, abrasion and cold flow) and high-grade (scratching, pitting/metal embedding and delamination) to assess the severity of the wear of polyethylene.

The rotating-platform group had a higher incidence of low-grade wear on the upper surface compared with the fixed-bearing group. By contrast, high-grade wear comprising scratching, pitting and third-body embedding was seen on the lower surface. Linear regression analysis showed a significant correlation of the wear scores between the upper and lower surfaces of the tibial insert ($R^2 = 0.29, p = 0.04$) for the rotating-platform group, but no significant correlation was found for the fixed-bearing counterpart.

This suggests that high-grade wear patterns on the upper surface are reduced with the rotating-platform design. However, the incidence of burnishing, pitting/third-body embedding and scratching wear patterns on the lower surface was higher compared with that in the fixed-bearing knee.

Analysis of wear of the articulating surface of ultrahigh-molecular-weight polyethylene (UHMWPE) from retrieved tibial components is an important method of assessing the clinical performance of total knee replacements (TKRs). Premature wear of UHMWPE tibial inserts is one of the major causes of failure of TKRs. Moreover, particulate wear debris released from polyethylene may also trigger a biological response resulting in osteolysis and/or aseptic loosening of the implant.

The contemporary tibial component in a TKR can either be a fixed- or a mobile-bearing design. The latter was introduced to provide congruity of the tibiofemoral articular surface and to allow relative movement between the lower surface of the polyethylene insert and the metal tibial baseplate for reduction of the constraint force. The contact stresses on the articular surface are theoretically reduced in mobile-bearing knees, thus potentially reducing the risk of polyethylene wear. These theoretical advantages have been evaluated in many biomechanical studies using experimental methods or studies using numerical models such as finite-element analyses. Although these experimental approaches allow calculation of the distribution and magnitude of stress in order to predict the risk of UHMWPE wear, prediction of specific wear patterns such as pitting and delamination resulting from material fatigue or the pattern of scratching caused by third-body embedded debris may still be difficult.

In this scenario, wear analysis of the failed polyethylene inserts would give objective observation and information on varying types of wear pattern in different types of prostheses.

The wear characteristics of the articular surface of tibial polyethylene inserts have been reported previously in a few retrieval studies. However, to the best of our knowledge, there has been no investigation of the relationship of the wear pattern of mobile-bearing rotating-platform and fixed-bearing TKRs. From the biomechanical point of view, the mobile-bearing rotating-platform design can reduce the contact stress on the upper articular surface. However, it has an additional backside articulation. Our hypothesis was that this design may have less severe wear on the upper articular surface, but may produce unexpected wear on the lower surface. Our aim was to analyse the wear patterns on the upper and lower surfaces of tibial inserts retrieved from rotating-platform and fixed-bearing polyethylene implants.
Patients and Methods
The components of 73 failed TKRs from 70 patients (65 women, 5 men; Table I) who underwent revision between 1997 and 2007 were retrieved. All the patients consented to the study which was approved by the hospital’s institutional review board.

The retrieved components were subdivided into rotating-platform and fixed-bearing groups. The former consisted of 15 knees with the low contact stress-rotating-platform prosthesis (LCS RP; DePuy, Warsaw, Indiana). There were 11 women and two men (one bilateral, one second revision due to instability) with a mean age at the time of revision of 69 (59.0 to 83.0). Knees with an LCS meniscal bearing tibial insert were excluded as this is a completely different type of insert making comparison difficult. None of the knees had breakage of the insert. The fixed-bearing group consisted of 22 knees with a Porous-Coated Anatomic prosthesis (PCA; Howmedica, Rutherford, New Jersey) and 36 with a Miller-Galante prosthesis (MG; Zimmer). There were 54 women and three men (one bilateral) in this group with a mean age of 70 (45.0 to 81.0).

The mean length of implantation was 121 (48.0 to 162.0) for the rotating-platform knees, 93.6 (48.0 to 180.0) for the PCA knees and 109 (50.0 to 156.0) for the MG knees. The mean body-weight was 72.8 kg (60.0 to 87.0) for the patients with a rotating-platform knee, 67.2 kg (45.0 to 92.0) for those with a PCA knee, and 73.5 kg (64.0 to 84.0) for those with an MG knee. There was no significant difference (p = 0.6, student t-test) in the body-weight between the rotating-platform and fixed-bearing groups.

All the knees had primary osteoarthritis at the time of their initial TKR. The reasons for revision surgery are shown in Table II.

The rotating-platform prosthesis was a posterior-cruciate-ligament-sacrificing design and had a curve-on-curve design for the tibiofemoral articular surface. The fixed-bearing implant was a posterior-cruciate-ligament-retaining design and had a relatively non-conforming flat-on-flat design for the tibiofemoral articular surface. All the inserts were made of UHMWPE. Based on the period in which the retrieved tibial inserts had been implanted, we were able to deduce that these components had been sterilised by gamma radiation in air. We did not obtain the dates of sterilisation from the manufacturers and thus could not provide the shelf-life data except for the mobile-bearing components in which the feedstock period was less than two years. All the retrieved femoral implants were made from cobalt-chrome alloy. The polyethylene inserts of the rotating-platform group were machined from polyethylene bar stock, which was ram-extruded using GUR 415 resin or 1050 resin. Dates of manufacture could not be determined for all the components, and therefore the specific resin designation for each insert could not be confirmed. For the

### Table I. Clinical details of the patients in the rotating-platform and fixed-bearing groups

<table>
<thead>
<tr>
<th>Design</th>
<th>Number</th>
<th>Female:male</th>
<th>Mean (SD; range) age at primary surgery (yrs)</th>
<th>Mean (SD; range) age at revision (yrs)</th>
<th>Mean (SD; range) body-weight (kg)</th>
<th>Mean (SD; range) length of implantation (mths)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>platform</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>LCS RP*</td>
<td>15</td>
<td>11:2</td>
<td>58.5 (7.4; 48.0 to 73.0)</td>
<td>69 (7.3; 59.0 to 83.0)</td>
<td>72.8 (7.3; 60.0 to 87.0)</td>
<td>121 (38.2; 48.0 to 162.0)</td>
</tr>
<tr>
<td>Fixed-bearing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PCA†</td>
<td>22</td>
<td>20:2</td>
<td>63.6 (7.1; 49.0 to 74.0)</td>
<td>73 (7.6; 57.0 to 81.0)</td>
<td>67.2 (13.8; 45.0 to 92.0)</td>
<td>93.6 (39.6; 48.0 to 180.0)</td>
</tr>
<tr>
<td>MG‡</td>
<td>36</td>
<td>34:1</td>
<td>58.9 (8.0; 40.0 to 74.0)</td>
<td>67 (8.1; 45.0 to 81.0)</td>
<td>73.5 (6.4; 64.0 to 84.0)</td>
<td>109 (31.3; 50.0 to 156.0)</td>
</tr>
</tbody>
</table>

* LCS RP, Low contact stress-rotating platform prosthesis  
† PCS, porous-coated anatomic  
‡ MG, Miller-Galante

### Table II. Primary diagnoses and reasons for revision as reported by retrieving surgeons

<table>
<thead>
<tr>
<th>Diagnosis/reason for revision surgery</th>
<th>Number of rotating-platform</th>
<th>Number of PCA†</th>
<th>Number of Miller-Galante</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of patellar component</td>
<td>4</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>Osteolysis/metallosis</td>
<td>3</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Loosening/instability</td>
<td>3</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>Polyethylene wear</td>
<td>1</td>
<td>7</td>
<td>11</td>
</tr>
<tr>
<td>Infection</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Pain</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>Others*</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>15</td>
<td>22</td>
<td>36</td>
</tr>
</tbody>
</table>

* factors causing failure of the knee components such as a fall or ligamentous rupture are listed as other factors  
† PCA, porous-coated anatomic
The wear score was calculated from the severity and area of wear. The scoring system was based on the worn area with a specific type of wear on the different zones of the tibial insert. The tibial articulating surface was divided into the medial and the lateral sides and each side was further divided into three equal zones anteroposteriorly. In order to quantify the worn area in each zone for different types of wear, a score of 0 to 3 was judged by two of the authors (FYH and TKC), who were blinded to the results. A total score for each type of wear was the sum of all the six zones.

The severity of wear of the inserts was assumed to correlate with the distribution of stress on the surfaces. The specific wear patterns were also expected to coincide with the levels of stress distribution. In order to distinguish between low-level and high-level wear, we divided the types of wear into two groups according to their mechanisms: low-grade (burnishing, abrasion and cold flow) and high-grade (scratching, pitting/metal embedding and delamination). Wear patterns and scores on the lower surfaces of the retrieved inserts were analysed by the same scoring system.

**Statistical analysis.** Linear regression analysis was performed to determine if details such as the length of implantation and weight of the patient and the thickness of the original component were associated with the extent of wear (total wear scores) to either the upper or lower surface. Regression analysis was also used to assess whether the wear scores at the upper surface were associated with those of the lower surface.

The wear scores of the rotating-platform and fixed-bearing groups were analysed by regression analysis and the analysis of variance (ANOVA) test using SPSS version 11.5 software (SPSS Inc., Chicago, Illinois). A p-value ≤ 0.05 was considered to be significant.

**Results**

**Wear patterns on the upper articular surface.** High grade wear patterns of scratching, pitting/metal embedding and delamination were more commonly seen on the upper surface in the fixed-bearing group than in the rotating-platform group. However, there were no significant differences for each wear pattern between the two groups (Table III; Fig.1). Low-grade wear patterns on the upper articular surface.
Wear patterns of burnishing, abrasion and cold flow were more common in the rotating-platform group than in the fixed-bearing group. The wear scores of the rotating-platform group for burnishing \((p = 0.002)\), and for cold flow \((p = 0.049)\) were significantly higher than those of the mobile bearing group. The total wear score of the upper articular surface was 108.6 for the rotating-platform group, which was significantly lower than that of the fixed-bearing group \((p = 0.002)\) (PCA, 160.9; MG 120.5).

**Wear patterns on the lower surface.** In contrast to the results seen on the upper articular surface, high-grade wear patterns were more commonly seen in the rotating-platform group (Fig. 2). The wear score on the lower surface of the rotating-platform group for scratching was significantly higher than those for the fixed-bearing group \((p < 0.001; \text{Table IV})\). As for pitting/embedding, the rotating-platform group was also significantly higher than those for the fixed-bearing counterpart \((p < 0.001)\). Curvilinear scratching with a slight burnishing wear pattern was also observed (Fig. 3a) on the lower surface of the rotating-platform group, but not in the fixed-bearing group. However, low-grade wear such as abrasion with slight pitting was more commonly seen in the fixed-bearing group (Table IV). The wear pattern was not significantly different in the two fixed-bearing designs (ANOVA test, \(p = 0.297\)) (Fig. 2). Protrusion of polyethylene into the screw holes and imprinting by the product marks of the base-plate were also observed in the fixed-bearing knees (Figs 3b and 3c). A severe wear pattern such as delamination was seen in very few cases on the lower surface of both groups and cold flow deformation was rarely seen.

Linear regression analysis (Table V) showed that there was a significant correlation between the damage score for the upper surface \((R^2 = 0.12, p = 0.01)\) and the length of implantation time for all the retrievals (Fig. 4). A positive correlation was found for the fixed-bearing group when comparing the wear score for the upper surface with the implantation time (PCA, \(R^2 = 0.4, p = 0.002\); MG: \(R^2 = 0.17, p = 0.02\)), this was not true for the rotating-platform group. However, no significant correlation was found when the wear score for the lower surface was compared with the length of implantation \((R, R^2 = 0.13, p = 0.25; \text{PCA}, R^2 = 0.00, p = 0.79; \text{MG}, R^2 = 0.02, p = 0.40)\), or the body-weight \((R, R^2 = 0.04, p = 0.54; \text{PCA}, R^2 = 0.00, p = 0.89; \text{MG}, R^2 = 0.00, p = 0.92)\) for either group. There was no significant correlation between the polyethylene thickness and the upper \((R, R^2 = 0.00, p = 0.97; \text{PCA}, R^2 = 0.04, p = 0.40; \text{MG}, R^2 = 0.01, p = 0.75)\) or lower \((R, R^2 = 0.00, p = 0.97; \text{PCA}, R^2 = 0.13, p = 0.11; \text{MG}, R^2 = 0.06, p = 0.65)\) surface wear score. A negative correlation was found for all the retrieved specimens \((R^2 = 0.04, p = 0.09)\) when independently comparing the wear scores for the lower surface with the thickness of the insert, but this was not statistically significant. In addition, we further

**Table IV.** The mean (SD, range) score on the lower surface for each wear pattern. The maximum score is 18 points

<table>
<thead>
<tr>
<th>Design</th>
<th>Low-grade wear</th>
<th>High-grade wear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Burnishing</td>
<td>Abrasion</td>
</tr>
<tr>
<td>Rotating platform</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LCS RP*</td>
<td>0.7 (2.6; 0.0 to 9.0)</td>
<td>0.4 (1.0; 0.0 to 3.0)</td>
</tr>
<tr>
<td>Fixed-bearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCA†</td>
<td>0.0</td>
<td>3.5 (4.2; 0.0 to 13.0)</td>
</tr>
<tr>
<td>MG‡</td>
<td>0.0</td>
<td>5.0 (2.8; 0.0 to 12.0)</td>
</tr>
</tbody>
</table>

* LCS RP, low contact stress-rotating platform
† PCA, porous-coated anatomic
‡ MG, Miller-Galante
analysed the correlation of the wear score of the upper and lower surfaces. There was a significant correlation ($R^2 = 0.29$, $p = 0.04$) for the rotating-platform group (Fig. 4b), but not for the fixed-bearing group (PCA, $R^2 = 0.02$, $p > 0.05$; MG, $R^2 = 0.001$, $p > 0.05$).

**Discussion**

The extent of polyethylene wear in modular TKRs is dependent on a number of factors, which include the design of the articular surface, the material used, the kinematics of the joint, the method of sterilisation and the
Although these variables are critical, another site of polyethylene wear is the lower surface of the insert.28 Polyethylene wear on the upper surface of the tibial insert has been described in many biomechanical studies15,16,18,23,29 and well-recognised in many retrieval studies.2,21,22,30 Most of the results from these studies show that a high conforming design reduces the contact stress and thus lowers UHMWPE fatigue and wear. However, there have been few studies which have examined wear patterns on the lower surface. A highly conforming articular surface with a moveable tibial insert in the rotating-platform design has given rise to the question of whether this design actually provides better wear resistance31,32 than the fixed-bearing design. This issue, however, may be considered as a trade-off effect. Our results support the hypothesis that polyethylene wear on the upper surface is reduced with the rotating-platform design, but there is also a higher incidence of high-grade wear patterns on the unconstrained lower surface.

Wear patterns on the upper surface. On the upper surface, high-grade wear patterns of delamination, pitting and scratching were seen more often in the fixed-bearing than in rotating-platform knees (p < 0.05). In contrast to the fixed-bearing knees, low-grade wear patterns of burnishing and cold flow were generally seen on the rotating-platform knees. This low-grade wear has been reported previously.15,16,18,23 Burnishing wear could be attributed to the highly conforming design and consequent reduction in polyethylene wear. The cold flow often seen in the rotating-platform group was considered to result from the lack of a boundary constraint of the tibial baseplate. In addition to conforming geometry, the kinematics of the tibial bearing also influence the wear pattern.27 Wear in the rotating-platform knee is theoretically reduced because the rolling/sliding curvilinear movement is separated from the transverse axial rotation movement on two separate articulating surfaces. This eliminates the cross-paths which cause higher wear in polyethylene as compared with the reciprocal linear or curvilinear paths.27,30 As for the non-conforming surface design of the fixed-bearing knee, the upper surface is required to accommodate all of the knee movements leading to multidirectional shear and high contact stresses on the surface of the polyethylene with the potential of severe or asymmetrical wear patterns.2 Lower rates of wear on the upper surface of the mobile knees may be explained by the decoupling of the rotational or translational movements which decrease the amount of multidirectional sliding as compared with the fixed-bearing knees.

Wear patterns on the lower surface. Although the rotating-platform group showed better wear resistance on the upper surface, wear patterns such as burnishing, scratching and pitting/third-body embedding were commonly seen on the lower surfaces. The rotating-platform metal baseplate which
has a polished surface (mean roughness value (Ra) ranging from 0.01 μm to 0.04 μm; mean scratch height (Rp) ranging from 0.05 μm to 0.14 μm), showed scratching patterns on the lower surface of the polyethylene and the upper surface of the baseplate (Fig. 3). The scratching pattern on the lower surface of the insert was curvilinear and possibly caused by the rotational movement against the baseplate. The rotating-platform design introduces an additional surface and also allows for third-body debris to invade this interface which could be further susceptible to wear. Similar wear patterns were also reported from previous retrieval studies. Although the biomechanical benefit of the rotating-platform knee is attractive, its clinical performance has yet to be proved. Modularity of the tibial component affords various options at the time of surgery, but the additional interface between a tibial insert and the baseplate creates an unintentional bearing surface. Micromovement at this interface is inevitable even for the fixed-bearing design and backside wear can be correlated with at this site. Therefore, modification of the locking mechanism for fixed-bearing knees to reduce micromovement or to create a new mechanism for mobile-bearing knees in order to inhibit the foreign particles from intruding into the interface is likely to be beneficial. The use of an all-polyethylene tibial component combined with moderate conformity without abrupt changes in tibiofemoral articular surface is further recommended for a primary TKR.

Our results showed a positive correlation for the rotating-platform group when we compared the wear score of the upper surface with that of the lower surface (R² = 0.29, p = 0.04; Fig. 4b). However, there was no statistical correlation for the fixed-bearing group. A similar trend was reported by Garcia et al. They concluded that higher levels of wear on the upper surface were found to be associated with higher levels of wear on the lower surface (R² = 0.25, p < 0.001). This finding allows us to speculate that the amount of movement of the insert contributes to the wear on the lower surface.

As for the fixed-bearing group, although some abrasion, pitting and embedded debris were evident, high-grade wear patterns such as scratching and delamination were less frequent on the lower surface. Wear patterns in the fixed-bearing group were similar and showed slight abrasion which was likely to be related to the texture of the metal surface. Protrusion of polyethylene into the screw holes and imprints by the marks or lettering of the base-plate were visible on the lower surface of the inserts, leading to the supposition that there may be relative movement taking place at this interface. Furthermore, embedded debris was seen on the lower surface of the inserts in the fixed-bearing group.

Different wear patterns observed in the rotating-platform and the fixed-bearing knees are related to their clinical performance. For the highly conforming design of the rotating-platform knee, a higher incidence of burnishing and abrasion wear patterns was commonly generated on the articular surfaces, and the wear patterns are likely to produce a large amount of smaller and granular particles, triggering a biological response and inducing osteolysis. With regard to the non-conforming design of the fixed-bearing knees, high-grade patterns of delamination, pitting and scratching commonly observed on the upper surface of the tibial insert produce larger shredded particles or large volumetric loss of material. Although the prevalence of osteolysis in the fixed-bearing knees has been shown to be lower than in the rotating-platform knees, more severe polyethylene wear (delamination) on the upper surface could result in deformity, instability and failure of the TKRs.

The use of either a fixed or a mobile bearing is still controversial. Well-designed fixed-bearing TKRs seem to give excellent results equivalent to those of the mobile-bearing designs. Although the biomechanical benefit of the
References


