Wear Damage in Mobile-bearing TKA is as Severe as That in Fixed-bearing TKA

Natalie H. Kelly BS, Rose H. Fu BS,
Timothy M. Wright PhD, Douglas E. Padgett MD

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Abstract

Background Mobile-bearing TKAs reportedly have no clinical superiority over fixed-bearing TKAs, but a potential benefit is improved polyethylene wear behavior.

Questions/purposes We asked whether extent of damage and wear patterns would be less severe on retrieved mobile-bearing TKAs than on fixed-bearing TKAs and if correlations with patient demographics could explain differences in extent or locations of damage.

Methods We performed damage grading and mapping of 48 mobile-bearing TKAs retrieved due to osteolysis/loosening, infection, stiffness, instability or malpositioning. Visual grading used stereomicroscopy to identify damage, and a grade was assigned based on extent and severity. Each damage mode was then mapped onto a photograph of the implant surface, and the area affected was calculated.

Results Marked wear damage occurred on both surfaces, with burnishing, scratching, and pitting the dominant modes. Damage occurred over a large portion of both surfaces, exceeding the available articular borders in nearly 30% of implants. Wear of mobile-bearing surfaces included marked third-body debris. Damage on tibiofemoral and mobile-bearing surfaces was not correlated with

patient BMI or component alignment. Damage on mobile-bearing surfaces was positively correlated with length of implantation and was greater in implants removed for osteolysis or instability than in those removed for stiffness or infection.

Conclusions Each bearing surface in mobile-bearing implants was damaged to an extent similar to that in fixed-bearing implants, making the combined damage score higher than that for fixed-bearing implants. Mobile-bearing TKAs did not improve wear damage, providing another argument against the superiority of these implants over fixed-bearing implants.

Introduction

TKA is the most effective treatment thus far for relieving pain and restoring function to patients suffering from advanced arthritis and other destructive knee problems. The continued success of TKA is due to improvements in surgical technique, bearing surfaces, and implant design. Implant designers have traditionally sought a balance between greater bearing surface congruity, which reduces polyethylene contact stresses but may increase stresses at fixation interfaces, and less conforming articulations, which reduce stresses placed upon fixation but are associated with greater contact stresses [18]. Excessive polyethylene contact stresses are responsible for wear and the release of particulate debris that can lead to osteolysis and subsequent loosening. Indeed, the long-term success of most TKAs will ultimately be determined by the extent of wear and damage to the bearing surface [15], and as such, attempts to improve bearing longevity are of paramount importance.

The concept of a mobile-bearing knee arthroplasty is an attempt to reach a satisfactory balance by combining both

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N. H. Kelly, R. H. Fu, T. M. Wright (✉), D. E. Padgett
Department of Biomechanics, Hospital for Special Surgery,
535 East 70th Street, New York, NY 10021, USA
e-mail: wrightt@hss.edu

design approaches: conforming tibiofemoral articular surfaces to decrease bearing contact stresses combined with bearing mobility to reduce stresses transmitted to the bone-implant interfaces [2]. Thus, mobile-bearing designs would not be as rotationally constraining as fixed conforming bearing implants and would provide increased motion clinically and improved knee kinematics of both femorotibial and patellofemoral articulations. In addition, maintenance of articulation congruity throughout the ROM would lead to lower wear rates and therefore improved durability.

The clinical results of mobile-bearing knee arthroplasties have generally been similar to those of fixed-bearing designs. In a recent prospective randomized study comparing mobile and fixed TKA designs, Gioe et al. [8] demonstrated no differences in the domains of clinical score, pain relief, or ROM. A recent meta-analysis of 33 studies assessing outcomes of 3532 TKAs [16] also suggested no difference in clinical or radiographic measures, such as clinical Knee Society score, clinical or functional American Knee Society score, ROM, activity, satisfaction, preference, radiographic alignment, osteolysis, wear, radiostereometric analysis measures, and complication rates between fixed- and mobile-bearing designs. Pagnano et al. [12], in another prospective randomized study, showed a rotating-platform design did not decrease the prevalence of lateral retinacular release or patellar tilt or subluxation and did not improve flexion or stair-climbing ability when compared with a posterior-stabilized, fixed-bearing knee. If no clinical superiority emerges from the use of mobile-bearing knee designs, the remaining potential advantage is one of improved wear damage behavior.

To examine this possible benefit, we first visually graded surface damage and then mapped that damage in retrieved mobile-bearing TKAs. We then correlated wear damage extent and location to patient demographics to determine whether those factors explained any increased damage.

Materials and Methods

The implant retrieval archive at our institution is an IRB-approved, HIPAA-compliant registry of almost 20,000 implants collected since 1977. From this collection, we examined all 48 retrieved mobile-bearing polyethylene tibial inserts (Low-Contact Stress [LCS®] [n = 12] and Press-Fit Condylar [PFC®] Sigma™ [n = 36]; DePuy, Warsaw, IN), 35 of which had been retrieved with the metallic femoral components and tibial trays. Twenty-two of the implants were cruciate-retaining, 25 were posterior-stabilized, and the remaining implant was of a constrained design. Ten had porous-coated metallic components for

biologic fixation; the other implants were cemented. All of the retrieved components had been from a primary TKA.

The clinical history, radiographs, and implants were reviewed for all cases. Length of implantation was 3 ± 2 years (mean $\pm$ SD) (range, 10 months to 12 years). Mean body mass index (BMI) was 30 (range, 16–45). Osteolysis or loosening (in 15 patients or 31% of the cohort) was the leading reason for revision, followed by stiffness (14, 29%), instability (nine, 19%), infection (nine, 19%), and malpositioning (one, 2%). Prerevision radiographs were available for all patients, and flexion/extension and varus/valgus alignment were measured from the lateral and AP radiographs, respectively. The mean tibiofemoral angle was $4^\circ \pm 4^\circ$ valgus, and the femoral and tibial angles measured $1^\circ \pm 4^\circ$ and $3^\circ \pm 4^\circ$ flexion, respectively.

Wear damage to the tibiofemoral articular and the tibial insert-tray mobile-bearing surfaces of the retrieved polyethylene tibial components was assessed using light stereomicroscopic analysis at magnifications from $\times 10$ to $\times 32$. The surfaces were both divided into 10 regions using a system by which wear damage assessments could be compared between the same regions on the articular and backside surfaces (Fig. 1). Assessments were made for each of seven wear damage modes: burnishing, scratching, pitting, delamination, surface deformation, abrasion, and third-body embedded debris. A scale of 0 to 3 was used to reflect the extent and severity of the damage; the scale of Hood et al. [9] has been used to identify damage by our group [19, 20] and others [5, 7, 10, 11, 14] since 1983. It is a subjective score that does not assess wear directly, but instead qualitatively identifies damage. The grade was assigned based on the area of coverage of the wear damage: a grade of 0 = no damage, 1 = less than 10%, 2 = 10% to 50%, and 3 = greater than 50%. If the damage was severe in a small area, the grade was increased by one to compensate for the severity. Grading was performed by one grader (RHF) blinded to the clinical and radiographic data. The extent of the wear damage was described by the total wear damage score, which was calculated by summing the scores for all seven modes across all 10 regions. The maximum score for each surface was 210 (10 regions $\times$ 3 maximum score $\times$ 7 damage modes).

The implant surfaces were then digitally photographed. The wear damage identified using the light microscope was manually replicated onto the digital projections of the surface (Fig. 2) using color-coded markings (Adobe® Photoshop® 7.0; Adobe Systems, Inc, San Jose, CA). Each identified wear mode was drawn as an individual layer, and the two-dimensional projected wear damage area of each layer was subsequently measured using ImageJ (National Institutes of Health, Bethesda, MD). The total available bearing surface areas on the articular and mobile-bearing surfaces were also measured. Wear damage on the articular

Fig. 1A–B (A) The tibiofemoral articular surface and (B) the mobile-bearing surface of the components were each divided into 10 sections. Wear damage grading scores were assigned for each section using light stereoscopic examination and a subjective grading score.

Fig. 2A–D Damage mapping was performed from digital photographs of (A) the tibiofemoral articular surface and (B) the mobile-bearing surface as a means of determining the amount of the available (C) tibiofemoral and (D) mobile-bearing surfaces experiencing wear damage (by the mode of damage observed). The color code corresponds to burnishing (gray), scratching (blue), third-body debris

(yellow), abrasion (purple), pitting (orange), delamination (green), and surface deformation (red). Black areas did not show wear damage. This implant was revised for infection in an 82-year-old man (with a BMI of 29) 3 years after it had been implanted. The damage score for the tibiofemoral surface was 39; the score for the mobile-bearing surface was also 39.

and mobile-bearing surfaces was measured individually. Overall wear damage areas for each of the modes were converted to percentages of the total possible contact area of the bearing (medial and lateral plateaus) and mobile-bearing surfaces. This was then used to estimate the extent of surface damage.

Scanning electron microscopy (SEM) was used to better visualize wear damage. Energy-dispersive spectroscopy (EDS) was used to determine the source of third-body debris embedded in the polyethylene. The bearing surfaces of the metallic tibial trays were also examined grossly and with light microscopy.

We used the Wilcoxon signed-rank test to examine differences in wear scores among regions on the surfaces since the data were not normally distributed. Differences in

wear damage scores based on reason for revision were tested using Student's *t* test. Linear regression analysis was used to examine the effects of clinical factors and radiographic alignment on wear scores and to compare total damage scores between the two surfaces.

Results

For the tibiofemoral articular surface, the total damage score was 38 ± 10 (range, 20–65), while that of the insert-tray mobile-bearing surface was 39 ± 13 (range, 22–67). The dominant damage modes on the tibiofemoral surface (Fig. 2A, C) and mobile-bearing surface (Fig. 2B, D) were scratching, burnishing, and pitting. Scratching was often

extensive, forming concentric rings over much of the mobile-bearing interface (Fig. 2B, D). The scratches varied in width up to a few millimeters and were often associated with pitting along the arc of the scratch. Third-body wear was associated with much of the damage to the mobile-bearing surfaces. SEM observations revealed scratches, and the accompanying appearance of pits on the polyethylene surfaces were the result of polymethylmethacrylate (PMMA) bone cement particles that had “walked” across the surface along a circular arc (Fig. 3A). EDS confirmed the debris was PMMA. For cases in which porous metallic coatings were employed for biologic fixation, metallic beads were also identified as a cause of third-body wear, with the metallic nature of the beads again confirmed with EDS (Fig. 3B). We found metallic beads in three of the 10 implants with porous-coated metallic components. The metallic tibial trays were also extensively damaged by third-body wear with similar concentric scratches (Fig. 4). No delamination damage was observed.

Wear damage was located over a large portion of both of the available surfaces (Fig. 5), with $91\% \pm 16\%$ of the tibiofemoral surface and $61\% \pm 32\%$ of the insert-tray mobile-bearing surface experiencing damage. The percentage of the articular surface that included wear damage equaled or exceeded 100% for 14 of the 48 retrieved tibial inserts, and eight inserts had wear damage across 90% or

more of the available mobile-bearing surface. Polyethylene scratching on the mobile-bearing surfaces was more severe ($p = 0.006$) in Regions 2 and 4, under the loaded plateaus, than in Regions 8 and 9. Linear regression analysis showed more severe wear damage (ie, higher wear scores) on the articular bearing surface correlated with ($r^2 = 0.39$,

Fig. 4 A photograph of the bearing surface on the superior metallic tibial tray shows severe scratching of the originally polished surface, with the scratches forming concentric rings around the center of the tray (seen in the upper part of the photograph).

Fig. 3A–B (A) A SEM photomicrograph (left) of the mobile-bearing surface shows embedded PMMA debris, and EDS analysis (right) of the PMMA particle at the top of the photomicrograph shows large amounts of zirconium, reflecting the zirconia used to render the PMMA radiopaque. (B) Another SEM photomicrograph (left) shows metallic beads embedded into the polyethylene mobile-bearing surface, and EDS (right) confirmed the presence of titanium and aluminum, consistent with the titanium alloy beads used for biologic fixation of the metallic component interfaces.

Fig. 5A–B Histograms of the percentage of the possible bearing surface demonstrating wear damage for (A) the tibiofemoral and (B) the mobile-bearing surfaces of the retrieved tibial components show damage extended over large portions of the surface, even beyond the intended tibiofemoral bearing surface for six of the components.

$p < 0.001$) more wear on the mobile-bearing surface. The tibial insert peg (the part of the mobile-bearing mechanism extending down into the hole in the peg of the metallic tibial tray) often showed burnishing in the anteroproximal region, consistent with contact with metallic tray-peg junction.

We found no correlation between the wear damage scores on the articular or mobile-bearing surfaces and patient BMI and no correlation between the wear damage scores on the articular surface and the length of implantation. However, the wear damage scores on the mobile-bearing surface correlated ($p = 0.023$) with length of implantation. Wear damage scores on the mobile-bearing surface were higher ($p = 0.001$) in implants removed for osteolysis or instability than in those removed for stiffness or infection.

Discussion

Mobile-bearing knee arthroplasty attempts to decrease the bearing contact stresses with conforming articular geometry while reducing the stresses transmitted to the bone-implant interface through bearing mobility. The decreased articular surface stresses should decrease wear, while the mobile-bearing should provide increased motion and improved kinematics. Clinical results of mobile-bearing implants have been similar to those of fixed-bearing implants in regard to clinical outcome scores, ROM, activity, satisfaction, wear, and complication rates [16]. To examine this possible benefit, we first visually graded surface damage and then mapped that damage in retrieved mobile-bearing TKAs. We then correlated wear damage

extent and location to patient demographics to determine whether those factors explained any increased damage.

Our study has several limitations. First, all implant retrieval studies have the limitation of examining failed devices, which might not represent well-functioning knee arthroplasties. This limitation cannot be avoided due to the difficulty in obtaining implants at the time of autopsy. A study that compared 24 implants removed at autopsy to 25 implants retrieved at reoperation using a similar damage-grading methodology did find lower wear scores in the autopsy group [14]. Therefore, the implants from our study are likely a worst-case example of wear damage. However, those implants removed for infection may be considered well functioning, and this cohort had average scores of 37 for the articular surface and 36 for the mobile-bearing surface, which are only slightly lower than the averages for the entire cohort. Second, damage mapping is performed on a two-dimensional projection and is not a three-dimensional measurement of wear. For the insert-tray surface, which is a flat articulation, this two-dimensional approximation is reasonable. The tibiofemoral articulation is biconcave but should also be reasonably well approximated by a two-dimensional projection. This method provides a qualitative percentage of the surface affected by a damage mode. When used in conjunction with the Hood damage scoring, it provides a description of both location and severity of damage. However, neither method measures wear (ie, the amount of material removed from the surface). To accurately measure wear, the preimplantation dimensions of the inserts would be necessary, and these were unavailable for this study. Third, our cohort had

nonuniform implant designs, polyethylene types, and sterilization methods. We had both LCS® and PFC® Sigma™ designs and a variety of constraints, including cruciate retaining, posterior stabilized, and one constrained post. Furthermore, we did not obtain data on the polyethylene resin and sterilization methods and how they may have changed over the range of dates in which these retrieved implants were manufactured. Four of the implants in our cohort were implanted in or before 1997 and thus were likely gamma sterilized in air as extrapolated from data collected on fixed-bearing PFC® implants by Fehring et al. [6]. The average wear damage scores for these four implants were 37.5 for both the tibiofemoral and insert-tray surfaces and thus were not different from the average of the entire cohort. Lastly, a more robust study design would include a cohort of fixed-bearing implants of a similar design. However, our main purpose was to qualitatively describe the severity and location of damage on mobile-bearing retrieved implants.

While we anticipated less wear damage from mobile bearings, the data did not confirm that notion. Indeed, the most striking finding from our retrieval analysis was the marked amount of wear damage occurring to the mobile-bearing surfaces, even in those implants not removed for reasons associated with wear. Of those 15 implants revised for the combined reasons of osteolysis and loosening, seven cases clearly listed osteolysis or poly wear as the reason for revision. These seven cases had an average length of implantation of 5.61 ± 4.00 years (range, 1.09–11.95 years). The development of osteolysis and noted poly wear at this relatively short implantation time may imply that

Fig. 6A–B (A) AP and (B) lateral radiographs show an implant revised after 3.8 years for tibial loosening and subsidence due to osteolysis.

there is increased wear debris burden resulting from this second bearing surface (Fig. 6). The amount and severity of the wear damage on the tibiofemoral surface, as reflected by our subjective grading, were similar to what was previously measured [9, 19, 20] in a number of fixed-bearing designs using the same techniques and scoring system within our retrieval analysis system (Table 1). The damage scores were, however, lower than those reported in the literature for the Porous-coated Anatomic (PCA[®]) design, but this implant had several design specifications and manufacturing processes that caused it to undergo severe surface damage and debris generation [20]. In general, the fact that the damage scores were comparable to older designs that were all gamma sterilized in air and were, in some cases, materials and designs that were ultimately abandoned, raises concerns for the amount of damage seen in these mobile-bearing implants. Since these earlier studies were performed over a span of 25 years, however, the results may not be directly comparable. Nonetheless, it provides an interesting historical perspective for the wear in the mobile-bearing designs. Furthermore, the amount and severity of wear damage on the mobile-bearing surface are comparable to those measured using similar regional wear damage scoring on fixed-bearing tibiofemoral surfaces (Table 1), suggesting this second bearing surface adds to rather than reduces the wear damage in these implants. Our observations confirm those of the other investigators who recently examined retrieved mobile-bearing implants [1, 5, 7, 10, 11]. These authors also reported burnishing and third-body debris as major causes of wear damage to mobile-bearing polyethylene components. Concentric rings of scratches and pits along arcs that exceeded the rotation that might occur during normal activities were common findings, with wear damage being often more severe in mobile-bearing components [5]. Pits in curvilinear lines paralleling the curved scratches suggest third-body debris particles rolled between the surfaces, repeatedly sinking into and being torn from the softer polyethylene. Lu et al. [11] examined wear damage on both surfaces of mobile-bearing and fixed-bearing implants and found more high-grade wear (delamination, pitting, and scratching) on the upper surface of fixed-bearing when compared to mobile-bearing implants. When examining the lower surface, however, mobile-bearing implants displayed more burnishing, scratching, and pitting/third-body embedded debris than the fixed-bearing implants [11].

When examining the location of the damage, many of the retrieved components showed burnishing across most of, if not more than, the available bearing surfaces on the tibial plateaus (Fig. 2C). Burnishing reflects the history of contact at the tibiofemoral surface [13], so burnishing beyond the bearing surface demonstrates patients were performing activities requiring more rotation and translation across the knee than was afforded by the tibiofemoral

Table 1. Comparison of wear damage scores by damage mode of several fixed-bearing TKAs to the mobile-bearing TKAs in our study

Study	Bearing type	Implant	Surface	Wear damage score						Total
				Embedded debris	Pitting	Scratching	Burnishing	Delamination	Surface deformation	
Hood et al. [9]	Fixed	PS TCP		1.2 ± 2.3	10.5 ± 6.7	12.5 ± 6.5	14.0 ± 6.8	0.0 ± 0.0	1.4 ± 1.8	40
Wright et al. [19]	Fixed	IB	Carbon fiber-reinforced	1.8 ± 3.4	7.9 ± 7.9	12.3 ± 5.3	13.4 ± 5.3	0.4 ± 1.1	0.9 ± 1.4	39.1
Wright et al. [20]	Fixed	PCA	Plain polyethylene	1.2 ± 2.3	10.5 ± 6.7	12.5 ± 6.5	14.0 ± 6.8	0.0 ± 0.0	1.4 ± 1.8	40
Kelly et al. [current study]	Mobile	LCS and PFC	Tibiofemoral	0.0 ± 0.0	13.7 ± 3.4	14.4 ± 4.9	16.2 ± 4.8	12.7 ± 6.8	7.9 ± 4.1	66.7
		Sigma		0.6 ± 1.1	9.9 ± 6.1	8.9 ± 4.6	18.1 ± 5.2	0.0 ± 0.0	0.1 ± 0.6	38.1
			Mobile bearing	0.4 ± 1.1	10.3 ± 7.4	14.2 ± 6.7	14.4 ± 7.0	0.0 ± 0.0	0.1 ± 0.4	39.4
			Both							77.5

Values are expressed as mean ± SD; PS TCP = posterior-stabilized total condylar prosthesis; IB = Insall-Burstein; PCA = Porous-Coated Anatomic; LCS = Low-Contact Stress; PFC = Press-Fit Condylar.

bearing surface. A recent study that examined the wear damage patterns of Exactech Optetrak® and Zimmer Insall-Burstein® II posterior-stabilized implants reported average wear damage areas of 83.1% and 69.6%, respectively [4]. The higher average wear damage (90.9%) for the tibiofemoral bearing surface in this study follows from the higher conformity of the bearing surface.

Our retrieval analysis of mobile-bearing TKAs showed a considerable amount of wear damage to both surfaces of the implants. These findings demonstrate the introduction of a second conforming bearing surface in mobile-bearing TKAs does not improve the wear damage behavior and must be considered another argument against the superiority of these implants compared to conventional fixed-bearing TKAs. Despite the fact that in vivo studies of patients with mobile-bearing knees using static radiographic and dynamic fluoroscopic studies [3, 17] show motion at the mobile-bearing surface during daily activities, this motion has not led to improved clinical outcomes or increased survivorship at followup times out to 23 years [12]. Our retrieval data serve to further question the use of this design, since it does not appear to reduce wear damage.

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