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Activity Level and Wear in Total Knee Arthroplasty

A Study of Autopsy Retrieved Specimens

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Abstract: We assessed the correlation between activity level, length of implantation (LOI), and wear in total knee arthroplasty. Twenty-eight implants were retrieved at autopsy from 8 men and 15 women. Linear, volumetric, and visual wear and the presence or absence of creep were quantitated. Functional level was classified using the Knee Society, the standard Charnley classification, and the UCLA activity level scale. The average age at surgery was 68 years ± 14.0 SD and average LOI was 74 months ± 38 SD. The average linear and volumetric wear rates were 0.127 mm/y ± 0.104 SD and 31.80 mm^3/y ± 42.8 SD. LOI (B coefficient = −0.656 ± 0.0 SE; $P<.001$) correlated with linear, volumetric, and visual wear rates. Charnley C patients showed decreased volumetric wear in the lateral compartment ($P=.01$). Decreased activity level (UCLA) correlated with areas of less extent and severity of creep ($P=.001$ and $P<.001$). **Key words:** total knee arthroplasty, polyethylene, wear, retrieval

One of the most important limiting factors in the long-term success of total knee arthroplasty (TKA) is polyethylene wear [1–9]. Particles of the ultra–high molecular weight polyethylene tibial inserts have been shown to elicit a foreign body response leading to the production of mediators of inflammation, which in turn produce bone resorption and osteolysis [10,11]. Osteolysis ultimately leads to loosening and component failure [12]. Multiple modes of wear and damage of artificial bearing surfaces used in TKA have been described in the literature [13]. Severity of wear has been associated with a combination of factors inherent to the device itself, such as design, manufacturing process, polyethylene thickness and size, sterilization process [14], and shelf life [15]. Patient characteristics, such as young age [16,17], weight, and activity level [11,16], as well as surgical factors, such as cement use, prosthesis alignment, and soft tissue balance, have been shown to influence the degree of wear of polyethylene total hip components. In contrast to total hip arthroplasties, in which wear can be measured radiographically quite accurately, a method of determining radiographic wear in TKAs does not exist. Studies on polyethylene wear in TKA have been limited mostly to implants retrieved at revision surgery [2,5,7]. TKA series have been limited mostly to reporting clinical results with little assessment on insert wear [18]. The amount of wear observed in clinically successful autopsy retrieved implants and its relationship to activity level have not been reported previously in the literature. In the present study, we assessed the correlation between activity level, length of implantation (LOI),

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and wear in TKA in polyethylene inserts retrieved at autopsy.

Materials and Methods

The patient cohort studied consisted of 22 nonconsecutive patients with 28 polyethylene inserts that had undergone primary TKA. All the specimens were obtained from an ongoing autopsy retrieval program at the John Hopkins University and patients consented for the retrieval before their death. All patients had received a primary Porous Coated Anatomic (PCA) prosthesis and had died with a clinically successful TKA. All of the inserts were of the nonconforming flat-on-flat design and manufactured using a surface heat pressing technique. Special care was taken to avoid damage of the polyethylene during removal at autopsy.

The retrieved specimens were obtained from 8 men and 15 women. The average age at surgery was 68 years ± 14 SD, and average LOI was 74 months ± 38 (range, 28–135 months). The average patient weight was 156.79 lb ± 35.83 SD. Preoperative diagnoses included osteoarthritis in 15 patients, rheumatoid arthritis in 6 patients, and osteonecrosis in 1 patient. Six knees were cemented, and the remaining knees were biologically fixed. Eleven inserts were 7 mm, 13 were 9 mm, and 4 were ≥11 mm in thickness. The shelf life was known for 20 of the 28 inserts: 1.1 years ± 0.6 SD (range, 0.34–2.3 years).

Office and hospital charts were reviewed, and patients were classified retrospectively with respect to medical and orthopaedic severity of illness and activity and functional level. American Society of Anesthesiologists' (ASA) physical status score [19] and Charlson Comorbidity index [20] were used as measures of medical severity of illness. The latter index gives patients a weighted score by taking into account the number as well as the severity of illness of each medical condition present at the time of surgery [20]. Orthopaedic severity of illness was assessed using the Charnley classification [21]. Functional status and activity level were assessed with the University of California Los Angeles (UCLA) activity scale (Table 1). All patients with bilateral surgeries underwent staged procedures, and each knee was analyzed as an individual patient because at the time of the second surgery Charnley and UCLA scores differed from scores assigned at the initial surgery.

The amount of linear, volumetric, and visual polyethylene wear was assessed on the retrieved specimens. Linear wear was calculated by measuring the most deformed or thinned area on each implant with a caliper. The measurements were taken from the medial and lateral sides of the insert. An unused identical insert was measured and used as control. The difference in linear thickness represented the amount of material lost or moved as a result of loading on the used inserts. A rating technique described by Hood et al [22] was used to assess visual wear. Fig. 1) shows the Hood zones. This technique involves inspecting all polyethylene and metallic components for evidence of fracture, deformation, and damage to articulating surfaces. Wear is classified from 0 to 3, in which 0 indicates no visible wear, and 3 indicates the most severe wear. The system was modified to include a separate score for the percentage of area involved. Wear on the nonarticulating portion of the insert (backside) was assessed with the same technique.

Volumetric wear was measured with a specially designed device that assessed dimensional changes in selected regions of the components. The device consisted of an X,Y positioning table outfitted with 3 precision linear voltage differential transducers (LVDTs) arranged along 3 mutually perpendicular axes. This allowed us to measure the surface coordinates of a component with respect to a fixed cartesian coordinate system. Volumes were computed for a rectangular grid measuring 0.75 × 1.15 inch. Reproducibility and accuracy with this system were calculated and established numerically within 1% to 0.5%. The grid was located over the surfaces that had the

Table 1. UCLA Activity Scale

Class	Description
1	Wholly inactive, dependent on others, and can not leave residence
2	Mostly inactive or restricted to minimum activities of daily living
3	Sometimes participates in mild activities, such as walking, limited housework, and limited shopping
4	Regularly participates in mild activities
5	Sometimes participates in moderate activities, such as swimming, or could do unlimited housework or shopping
6	Regularly participates in moderate activities
7	Regularly participates in active events, such as bicycling
8	Regularly participates in active events, such as bowling or golf
9	Sometimes participates in impact sports, such as jogging, tennis, skiing, acrobatics, ballet, heavy labor, or backpacking
10	Regularly participates in impact sports

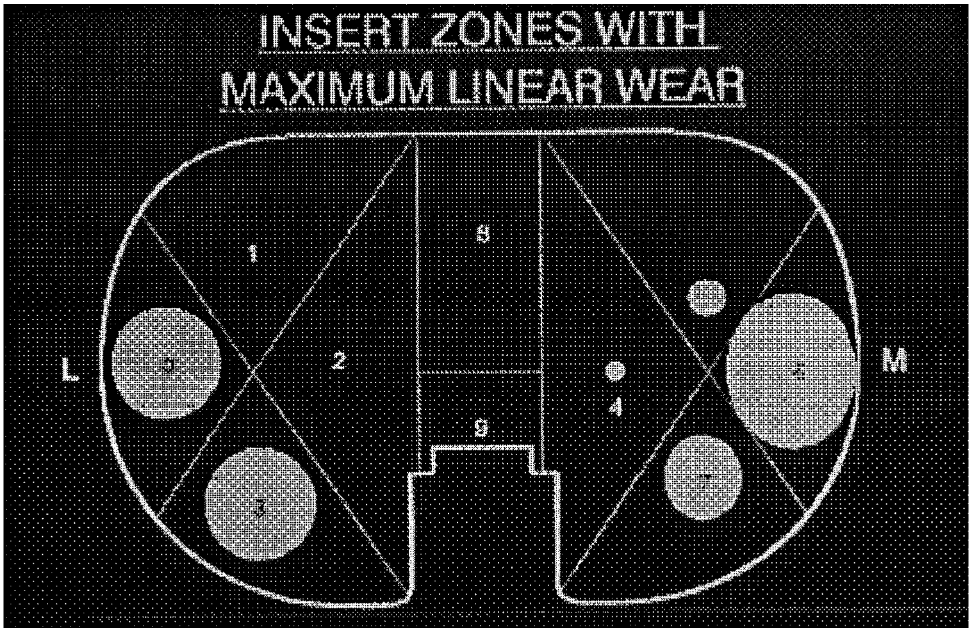

Fig. 1. Hood zones to assess visual wear. Insert zones with maximum linear wear.

largest apparent dimensional change, and measurements were taken. Unused inserts, identical to those implanted, were used as a control to assess the volumetric changes of the used inserts.

Wear rates were calculated by dividing the amount of linear and volumetric wear by the LOI:

$$\text{Linear or volumetric wear rate (mm or mm}^3\text{/yr)} = \frac{\text{Linear or volumetric wear}}{\text{LOI (y)}}$$

On our calculation of wear rates, we have assumed that wear is a linear function. Wear most likely is not a linear phenomenon. The *bedding in* that occurs when the inserts are constrained minimally probably occurs as a result of the creep of the polyethylene. We believe that during the period of this study, averaging out the wear rate reflects the actual physical phenomenon occurring in these inserts during an average implantation time of 74 months.

All statistical analyses were performed using SPSS 8.0 for Windows (Chicago, IL). Descriptive statistics were obtained on all variables collected during the study before their inclusion in the statistical analyses, and appropriate transformations were used to normalize data, if necessary, for nonparametric statistical testing, as shown in Table 2. The continuous variables included patient factors, such as weight and age, as well as measurements obtained for linear and volumetric wear and wear rates. Pearson and Spearman correlation coefficients and analysis of variance (ANOVA) if necessary were used to analyze the relationship among these variables. $P<.05$ was considered statistically significant.

Results

Preoperatively, 13 patients' knees were classified as Charnley A, 4 were B, and 11 were C. According

Table 2. Transformation of Continuous Variables to Nominal Data for Nonparametric Statistical Analyses

	Continuous Variable	Nominal Variable
Charlson Comorbidity Index	0	0
	1	1
	≥2	2
ASA score	No transformations were performed	
UCLA Activity Scale	Class 1	1
	Class 2	2
	Class 3 or 4	3
	Class 5 or 6	4
Charnley class	No transformations were performed	

ASA, American Society of Anesthesiologists.

to the UCLA activity scale preoperatively, 2 patients were wholly inactive, dependent on others, and could not leave their residence (group 1); 5 patients were mostly inactive or restricted to minimal activities of daily living (group 2); 17 patients sometimes or regularly participated in mild activities, such as walking, limited housework, and limited shopping (group 3); and 3 patients sometimes or regularly participated in moderate activities, such as swimming, or could do unlimited housework or shopping (group 4) (1 missing). Postoperatively, 6 patients were mostly inactive or restricted to minimal activities of daily living (group 2); 12 patients sometimes or regularly participated in mild activities, such as walking, limited housework, and limited shopping (group 3); and 7 patients sometimes or regularly participated in moderate activities, such as swimming, or could do unlimited housework or shopping (group 4) (3 missing). The average Charlson comorbidity index score was 1.36. Seven patients had no associated medical comorbidities. Nine patients had a Charlson comorbidity index of 1, and 9 patients had a score of ≥2. Preoperatively, 21 patients had an ASA physical status score of 2, and 6 patients had a score of 3. No patients were classified as 1, 4, or 5 (1 missing). The average preoperative Knee Society pain score was 38. The average postoperative pain score at last follow-up was 96. The average Knee Society function score preoperatively and postoperatively was 38 and 82.

The average preoperative and postoperative mechanical deformity was 2° of varus (range, 28° of varus to 20° of valgus) and 1° of varus (range, 6° of valgus to 5° of varus). At the time of death, the knees had been *in situ* for a mean of 74.5 months. Of 28 knees, 16 had >5 years of follow-up, and 6 had >10 years of follow-up.

The commonest form of wear identified was burnishing followed by delamination and subsurface cracking. Hood zones 0 and 3 in the medial and 6 and 7 in the lateral side of the articulating surface appeared to have the highest creep or deformation in severity and percent of the area involved. Of the 28 knees, 18 had a score of ≥2 in at least 1 of the Hood zones. In the insert's backside, the commonest form of wear was burnishing, occurring on the medial and lateral peripheral areas (Hood zones 0 and 6).

The average linear wear in the medial compartment was 0.67 ± 0.54 mm and in the lateral compartment was 0.67± 0.58 mm. The average volumetric wear in the medial compartment was 127.88± 65 mm^3 and in the lateral compartment was 126.8 ± 100.25 mm^3. The average linear and volumetric wear rates were 0.127 mm/y ± 0.104 SD and 31.80 mm^3/y ± 42.8 SD (Table 3).

There was a direct correlation between LOI and volumetric (r^2 = −0.595; P=.003), visual (r^2 = −0.694; P<.001), and linear wear rates (r^2 = −0.527; P=.005). As LOI increased, there was a statistically significant decrease in linear, volumetric, and visual wear rates (Fig. 2). Table 4 shows the P values corresponding to the correlations between the variables included in the study and volumetric and linear wear and wear rates. There was a statistically significant association between Charnley scores, age (P=.003), and weight (P=.04). Patients classified as Charnley C were statistically significantly younger and weighed less than patients classified as Charnley A or B. These patients also showed less volumetric wear in the lateral compartment (P=.01) and a trend toward less creep or deformation on their implants (P=.07).

When the ANOVA was performed, the most important predictor of volumetric wear in the medial compartment was weight (coefficient = 0.946 ± 0.303 SE; P=.01). Patients in UCLA scale group 4 had statistically significantly higher creep or deformation of implants in severity (P<.001) as well as in extent (%) (P=.001) of involvement. Stepwise multiple regression analysis showed that UCLA score was the most important predictor of extent (%) of involvement of deformation (coefficient = 1.841 ± 0.835 SE; P=.039). When assessing the creep and wear issues in our cohort of patients, the multivariate regression showed that volumetric wear is affected mostly by weight, and the creep or deformation factor is affected mostly by the patient's activity.

Discussion

Numerous studies have been published on insert wear in total hip arthroplasty and TKA [7,9,17,23]. Acetabular polyethylene wear has been measured on autopsy retrieved components, and *in vivo* wear rates have been calculated [24,25]. These studies have associated increased wear with prosthesis design, material issues [9,26], 32-mm head sizes [24,25], titanium bearing surfaces, and polyethyl-

Table 3. Mean Volumetric and Linear Wear Rates

Wear Rates	Mean ± SD
Linear	0.1274 ± 0.1040 mm/yr
Volumetric	31.80 ± 42.76 mm^3/yr

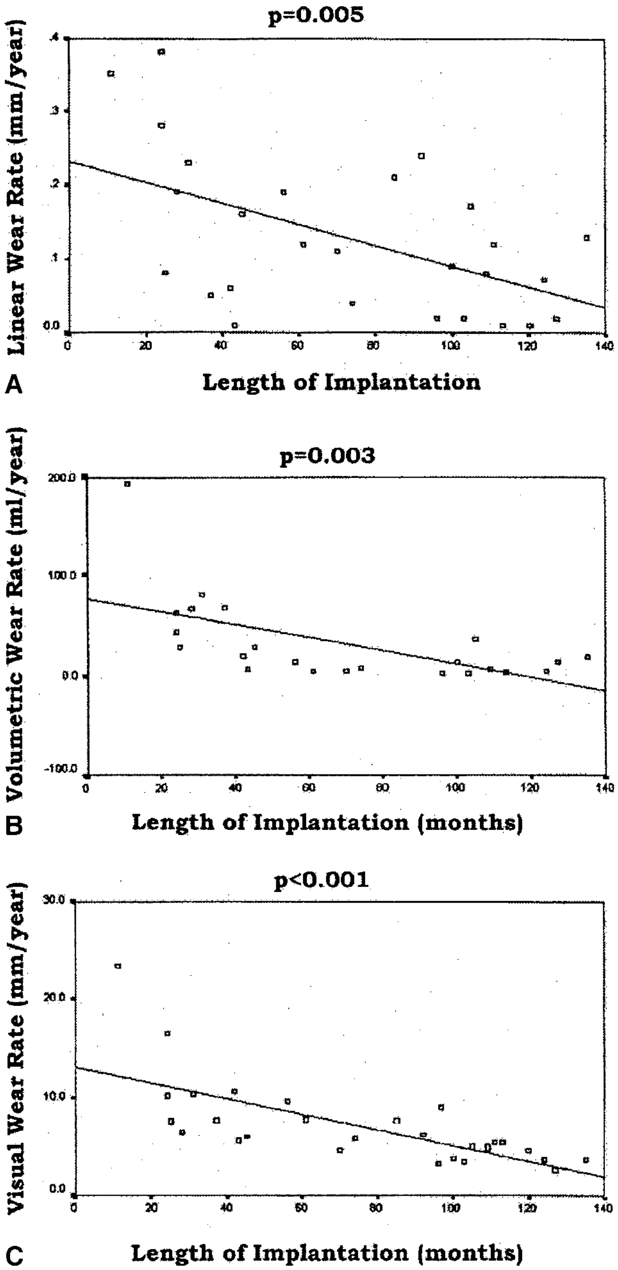

Fig. 2. (A) Mean linear wear rate versus length of implantation (p=.005). (B) Mean volumetric wear rate versus length of implantation (p=.003). (C) Mean visual wear rate versus length of implantation (p<.001).

ene quality and thickness [9,17,27]. Age and activity level have been reported to be important factors influencing wear and overall survival of the artificial joint [13,16,28,29].

Using a pedometer, investigators have assessed the activity level of patients with a total hip arthroplasty or TKA [28]. Activity level as measured by steps per day is extremely variable. Schmalzried et al [28] reported that a patient with a hip or knee arthroplasty averages 4,988 steps/d (range, 395–17,718 steps/d), which accounts for approximately 0.9 million cycles/y. In this same study, TKA patients averaged 3,514 steps/d, or 0.6 million cycles/y. Wallbridge and Dowson [16] used a pedometer to study the walking activity of a cohort of 11 patients with a total hip arthroplasty or a hemiarthroplasty and reported a mean number of cycles per day of 3,975, or 1.45 million cycles/y. These studies showed that activity levels in patients with artificial joints are extremely variable. In one study, the most active patient walked 45 times more than the least active patient.

Zahiri et al [29] compared the quantitative assessment of walking activity of joint arthroplasty patients as measured by pedometer, with qualitative patient activity instruments, such as the UCLA activity scale and the activity visual analog scale. The study reports a strong correlation between average steps per day and the UCLA activity scale (P=.002). According to their figures, our series of patients averaged approximately 3,750 steps/d (plotting UCLA score vs steps per day). This average is comparable to what has been reported by Schmalzried et al [28].

The aforementioned studies show a strong relationship between actual activities as measured by physical means to a questionnaire developed by the UCLA group. Prior studies suggested the relationship between wear and activity level.

Although the UCLA Activity Scale Rating on our cohort of patients was performed retrospectively, the 2 senior authors (K.K., D.S.H.) have kept a joint registry at Johns Hopkins for 30 years. The details that the senior authors maintained in the record keeping as well as in the history taking on the patients preoperatively allowed us to perform an accurate assessment of the UCLA Activity Level Score from a current review.

To our knowledge, our results are the first to show in autopsy retrieved implants from successful implants that patients with higher activity levels assessed by the UCLA activity scale had larger areas with involvement of creep or deformation (P=.001) and increased severity of involvement (P<.001) than those with less activity. Patients in group 4 differed statistically from the remaining groups. Schmalzried et al [28] also reported a tendency toward greater activity as assessed by pedometer in patients classified as Charnley A (approximately 1,000 steps more than class B or C). Our results show a statistically significant correlation between Charnley class A and volumetric wear in the lateral compartment (P=.01) and a trend toward greater

Table 4. Correlations Between Patient Parameters, Linear and Volumetric Wear and Wear Rates, and Creep/Deformation Extent and Severity

	Linear Wear (M, L, and W Rate)	Volumetric Wear (M, L, and W Rate)	Extent of C/D	Severity of C/D
Sex				
M = 8	M = .43	M = .76		
F = 15	L = .34	L = .38	.68	.67
	WR = .91	WR = .72		
Age				
<60 = 7	M = .72	M = .14		
>60 = 21	L = .37	L = .82	.41	.59
	WR = .42	WR = .09		
Weight	M = .53	M = .005		
	L = .73	L = .46	.94	.85
	WR = .49	WR = .48		
Charnley	M = .26	M = .7		
class	L = .27	L = .01	.12	.07
	WR = .8	WR = .3		
Charlson	M = .9	M = .43		
Index	L = .53	L = .07	.33	.26
	WR = .13	WR = .36		
UCLA score				
Preoperative	M = .19	M = .11		
	L = .13	L = .56	<.001	.001
	WR = .6	WR = .8		
Postoperative	M = .53	M = .7		
	L = .1	L = .3	.36	.28
	WR = .4	WR = .58		
ASA score	M = .5	M = .4		
	L = .66	L = .5	.41	.41
	WR = .5	WR = .58		
KS function score				
Preoperative	M = .37	M = .13		
	L = .44	L = .86	.73	.88
	WR = .32	WR = .37		
Postoperative	M = .89	M = .41		
	L = .62	L = .49	.37	.44
	WR = .16	WR = .61		

NOTE. Only *P* values are shown.
M, medial compartment; L, lateral compartment; WR, average wear rate; C/D, creep/deformation; ASA, American Society of Anesthesiologists; KS, Knee Society.

severity of creep in this group (P=.07). This lack of statistical significance probably is due to the small number of patients in our cohort. We believe that Charnley classification used as a measure of activity level may be a predictor of *in vivo* wear. The Charnley classification is a rudimentary combined measure of orthopaedic and medical severity of illness, however, and a more specific outcome instrument that measures activity level and disease severity should be developed.

Diduch et al [18] reported survival rates between 87% and 94% at 18 years in patients <55 years old. The patients in this study were quite active; one fourth participated in strenuous activities, such as farm or construction work, or participated in competitive sports, such as cycling, skiing, or tennis. Of the patients in this study, 60% regularly walked for a distance of 2 miles. Kuklo et al [30] also reported a 100% survival rate after 6 TKAs in 5 active-duty soldiers at an average follow-up of 3 years. This report attempted to correlate activity level but numerically did not assign a value to it or correlated the revision rates with the pedometer-like results.

Young patients with a TKA have been reported to lead more active lifestyles than older patients with a TKA [28]. Schmalzried et al [28] showed a statistically significant difference in activity level according to age. They reported that patients >60 years old averaged 4,400 steps/d (0.8 million cycles/y), whereas patients <60 years old averaged 5,732 steps/d (1.046 million cycles/y). Men <60 years old were found to be the most active. This was not the case in our cohort. In our study, 7 patients were <60 years old at the time of surgery, and all were classified as Charnley C ($P<.001$). Although younger, these patients had lower wear rates than patients in other Charnley classes. In our cohort of patients, these patients had a Charlson comorbid index score of 2.14 compared with 0.95 in patients >60 years old ($P=.037$) and were significantly less active than the older patients. These results support a strong relationship between activity and wear and downplay the age factor. This issue is significant in inflammatory conditions, such as rheumatoid arthritis and lupus, in which the disease incidence curve peaks at a young age. It is probably misleading to assess any type of wear rates or wear patterns strictly based on age. Current protocols for implant selection (demand matching), such as those proposed by Iorio et al [31], that rely strongly on age should be modified to reflect this important finding. Covariable analyses need to be performed on patients or any series attempting to quantify relationships between ages, wear rates, and activity level.

Our results show that LOI is the most important predictor of linear and volumetric wear rates in autopsy retrieved implants. As LOI increased, wear rates decreased. LOI is difficult to analyze separately from implant factors as well as activity level or age. This is true especially for our cohort of young patients, who appeared to be medically sicker and had lower activity levels than the older cohort of patients. The average time from implantation to death in our patients was approximately 6 years, much lower than the life expectancy for age-matched individuals, which should have been approximately 17 years. A possible explanation for the observed decrease in wear rates is that as LOI increased, our cohort grew older and sicker and most likely decreased activity level. Another possible explanation for this decrease in wear rates could be related to implant design. The starting flat-on-flat configuration of the femoral component on the tibial component probably became more conforming with time as polyethylene wear and deformation coupled the femoral component with the tibial insert. This change converted an unfavorable bearing surface into a more congruent couple.

Polyethylene, as a material in joint arthroplasty, has been reported to undergo creep as well as wear. Creep is a mechanical process through which the material undergoes cold flow. The significance of creep on total joint arthroplasty design has been addressed in many publications. Our results show that creep in TKA inserts is the most important variable that should be taken into account when designing a device for patients in the higher activity level bracket. The creep and deformation showed a statistically significant correlation between the activity level as measured by the UCLA scale and severity ($P=.001$) as well as the percent of area involved ($P<.001$). We believe this is an important finding that has not been reported previously.

Conclusions

1. Activity level correlated with deformation and creep patterns in polyethylene inserts in TKAs with this particular design.
2. Age and activity level showed little correlation.

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