The 2012 Frank Stinchfield Award

Decreasing Patient Activity With Aging

Implications for Crosslinked Polyethylene Wear

Andrew K. Battenberg BS, Jeffrey S. Hopkins MD,
Andrew D. Kupiec, Thomas P. Schmalzried MD

Published online: 3 August 2012
© The Association of Bone and Joint Surgeons® 2012

Abstract

Background Patient activity influences polyethylene wear. However, it is unclear how individual activity changes with patient aging after THA.

Questions/purposes We quantified changes in individual gait cycles and gait speed, assessed age-related differences in these parameters, and determined their relationship to polyethylene wear.

The institution of one of the authors (TPS) has received funding, during the study period, from the Piedmont Foundation (Rolling Hills, CA, USA)

All ICMJE Conflict of Interest Forms for authors and *Clinical Orthopaedics and Related Research* editors and board members are on file with the publication and can be viewed on request. *Clinical Orthopaedics and Related Research* neither advocates nor endorses the use of any treatment, drug, or device. Readers are encouraged to always seek additional information, including FDA approval status, of any drug or device before clinical use. Each author certifies that his or her institution approved the human protocol for this investigation, that all investigations were conducted in conformity with ethical principles of research, and that informed consent for participation in the study was obtained. This work was performed at St Vincent Medical Center, Los Angeles, CA, USA.

A. K. Battenberg (✉)
David Geffen School of Medicine at UCLA,
10833 Le Conte Avenue, Los Angeles,
CA 90095, USA
e-mail: akbatten@gmail.com

J. S. Hopkins, A. D. Kupiec
Joint Replacement Institute at St. Vincent
Medical Center, Los Angeles, CA, USA

T. P. Schmalzried
Department of Orthopaedic Surgery, Harbor-UCLA
Medical Center, Torrance, CA, USA

Methods A microprocessor was worn on the ankle to quantify the activity of 14 healthy patients with a well-functioning THA at two time periods: early (within 3.5 years of implantation) and late (10–13 postoperative years). Wear was measured on serial radiographs using edge detection-based software.

Results Mean activity decreased by 16% from the early to the late period: 2.04 million gait cycles/year to 1.71 million gait cycles/year. Mean gait speed decreased by 9%: 15.4 cycles/minute to 14.0 cycles/minute. The activity of the 10 patients who were younger than 65 years at surgery decreased by 14% (2.34 million gait cycles/year to 2.02 million gait cycles/year), while the four patients 65 years or older at surgery decreased by 28% (1.29 million gait cycles/year to 0.94 million gait cycles/year). Gait speed was 26% slower for patients 65 years or older than for patients younger than 65 years. The mean linear penetration rate decreased by 42% from the first 5 years (early wear rate) to the next 8 years (late wear rate, 5–13 years): 0.043 mm/year to 0.025 mm/year.

Conclusions The greatest patient activity and wear occurred during the first 5 years. Walking speed and gait cycles both decreased with aging, resulting in decreasing wear over time.

Introduction

Over the past decade, the focus of hip arthroplasty has been the efficacy of various bearing surfaces, with the goal of minimizing revision surgery related to the bearing [3–5]. Patient activity is a critical variable that influences wear and the survival of joint arthroplasty [11]. In a pedometer study of 111 patients with well-functioning total joint arthroplasties, age was negatively correlated to activity [12]. Using a two-dimensional accelerometer worn on the ankle, the activity of 33 healthy patients with well-functioning THAs averaged 1.9 million cycles/year [15]. In another study of

37 hips using the same methodology, joint use was related to wear of noncrosslinked polyethylene at the 90% confidence level. Without three recognized outliers, wear was highly correlated ($p < 0.0001$) to joint use [11].

The intermediate-term results of crosslinked polyethylene are encouraging: low clinical wear rates and little to no osteolysis [1, 5–7]. However, there have been no studies assessing the relationship between patient activity and the wear of crosslinked polyethylene. Further, little is known about how individual activity changes with patient aging.

We therefore asked: (1) How does individual patient activity (measured as gait cycles) change with time? (2) How does gait speed change with time? (3) Are there age-related differences in activity and gait speed? And (4) do aging-related changes in activity influence polyethylene wear?

Patients and Methods

Between 1993 and 2011, we measured the activity of 276 patients who had a primary THA: 265 were assessed

Table 1. Patient demographics

Variable	Value
Age at surgery (years)	55 ± 14.3 (26–78)
Followup (years)	11.4 ± 0.7 (10.3–12.9)
Height (cm)	167 ± 12.9 (140–185)
Weight (kg)	83 ± 18 (50–104)
BMI	29.6 ± 5.3 (21.5–38.5)

Values are expressed as mean ± SD, with range in parentheses.

using an electronic digital pedometer at the belt line (330 Pedometer; Sportline, Campbell, CA, USA) and 102 were assessed using a microprocessor with a two-dimensional accelerometer worn on the ankle (StepWatch™ Activity Monitor [SAM]; Cyma Corp, Seattle, WA, USA). All patients were community ambulators with well-functioning hip prostheses; their activity was not limited by the function of the prosthetic hip(s). The essential criterion for inclusion was willingness by the patient to comply with and complete the activity assessment protocol. There were no specific exclusion criteria.

Two hundred thirty-five of the 276 patients had a unilateral primary THA. Among these, there were 14 Charnley Class A [2] patients with 14 well-functioning primary THAs implanted by the same surgeon (TPS) with the same 5-Mrad crosslinked and remelted polyethylene liner (Marathon®; DePuy Orthopaedics, Inc, Warsaw, IN, USA; FDA-approved for this use) (Table 1). All patients had two postoperative activity measurements: early (mean, 1.5 years; SD, 1.0 years; range, 0.5–3.5 years) and late (mean, 11.1 years; SD, 0.7 years; range, 10.0–12.3 years). The average age of these 14 patients at the time of surgery was 55 years; 10 of these patients were younger than 65 years at the time of surgery and four were 65 years or older. There were no activity restrictions for these four men and 10 women. The average height was 167 cm, the average weight was 83 kg, and the average BMI was 29.6.

All hips had modular cementless acetabular components (Duraloc®; DePuy Orthopaedics, Inc; FDA-approved for this use) (Table 2). The average outer diameter of the acetabular components was 56 mm (range, 52–62 mm). The lateral opening angle averaged 46° (SD, 5°; range,

Table 2. Patient components

Patient	Liner	Acetabular component				Femoral head component	
		Design	Material	Size (mm)	Cup inclination (°)	Material	Size (mm)
1	Marathon®	Duraloc® Sector™	Ti	60	47	Zi	28
2	Marathon®	Duraloc® 300	Ti	58	49	CoCr	32
3	Marathon®	Duraloc® Sector™	Ti	54	47	Zi	28
4	Marathon®	Duraloc® Sector™	Ti	58	37	CoCr	28
5	Marathon®	Duraloc® Sector™	Ti	54	45	CoCr	32
6	Marathon®	Duraloc® Sector™	Ti	58	48	CoCr	28
7	Marathon®	Duraloc® 100	Ti	62	42	CoCr	28
8	Marathon®	Duraloc® 300	Ti	62	39	CoCr	28
9	Marathon®	Duraloc® 300	Ti	52	50	CoCr	28
10	Marathon®	Duraloc® Sector™	Ti	54	40	CoCr	28
11	Marathon®	Duraloc® 300	Ti	54	53	CoCr	28
12	Marathon®	Duraloc® 300	Ti	54	54	CoCr	28
13	Marathon®	Duraloc® Sector™	Ti	58	48	CoCr	32
14	Marathon®	Duraloc® Sector™	Ti	56	47	CoCr	28

37°–54°). Femoral head size was 28 mm in 11 hips and 32 mm in three hips.

The SAM is a microprocessor with a two-dimensional accelerometer and random access memory (Fig. 1). The SAM was designed specifically to measure lower-extremity movements, including walking, running, stair use, and bicycling. It is about the size and weight of a pager and has the capacity to measure and record gait cycles minute by minute for up to 28 days of continuous activity. One gait cycle begins at initial heel strike of the leg wearing the SAM device and ends with the leg's next heel strike. Additional derivatives include analysis of walking speed (Fig. 2). Compared to the electronic digital pedometer worn on the belt line, the SAM is more accurate (mean absolute error: 2.8% versus 0.5%) [13]. The details of each method have been reported previously [11–13]. Each patient was individually instructed in the use of the device(s), and one of the investigators checked and optimized the function of the device(s) on each patient. The SAM was worn on the ankle for a minimum of 5 days (mean, 9.2 days; SD, 4.6 days; maximum, 30 days) during both the early and late activity assessment periods [14]. To calculate total cycles at latest followup, the average of a patient's early and late activity rate was multiplied by the number of years elapsed from surgery to the latest activity assessment. Gait speed, defined as the total number of cycles recorded divided by the total time the patient was active, was reported as cycles/minute. The SAM files were downloaded into a statistical analysis package (STATA®; StataCorp LP, College Station, TX, USA).

Two of the authors (AKB, JSH) measured linear head penetration and volumetric wear on serial AP radiographs of the pelvis, using the validated two-dimensional, edge detection-based computer algorithm of Martell and Berdia [8], which is accurate and reproducible. The two observers

Fig. 1 The SAM is a microprocessor with a two-dimensional accelerometer and random access memory. About the size and weight of a pager, the SAM measures and records the motion of the leg in real time for up to 28 days.

received validation after analyzing a series of 25 standardized radiographs provided by the software developer; each radiograph was analyzed over three measurement periods to confirm precision, and accuracy was confirmed by comparison with standardized measurements from the software developer. All study images were measured three times by each observer during different sessions, and measured values were averaged between observers. Wear rates were calculated via linear regression analysis of the average measurements obtained for a given hip. Early wear rate was determined using all radiographs from 1 to 5 years postoperatively and late wear rate using radiographs from 5 to 13 years postoperatively. Each hip had at least three radiographs (mean, 5.2; maximum, nine) after the 1-year radiograph. Adjusted wear rate was defined as the wear rate/million gait cycles for a 70-kg patient weight [1, 11].

We determined differences in activity and gait speed between the early and late time periods using a paired Student's t-test. We determined correlations in individual activity between the early and late time periods using a Pearson correlation (*r*). The differences in activity and gait speed between the early and late time periods of two age groups (younger than 65 years versus 65 years or older)

Fig. 2A–B Individual SAM minute-by-minute output data are shown. This output allows calculation of number of gait cycles per unit time, active and inactive times, number of starts, total number of gait cycles, and gait speed. **(A)** This patient averaged 3372 cycles/day at 14.5 cycles/minute. **(B)** This patient averaged 8058 cycles/day at 22.2 cycles/minute.

were determined with a univariate analysis using a two-sample homoscedastic Student's *t*-test. We determined differences in wear rates between the early and late time periods using a paired Student's *t*-test. We determined correlations in individual wear rates between the early and late time periods using a Pearson correlation (*r*). Statistical analyses were performed using Excel[®] (Version 12.0.0; Microsoft Corp, Redmond, WA, USA).

Results

During the early period (first 5 years), the average number of gait cycles/day was 5599 ± 2511 (range, 2094–10,717), which extrapolates to 2.04 million gait cycles/year. In the late period (≥ 10 years), the average number of gait cycles/day was 4678 ± 2393 (range, 7374–8055), which extrapolates to 1.71 million gait cycles/year, a 16% decrease from the early period ($p = 0.006$) (Table 3, Fig. 3). Early and late individual activity rates were correlated ($r = 0.88$, $p < 0.0001$). The linear regression equation for activity was millions of gait cycles/year = $3.29 - (0.023 \times \text{age of the patient in years at surgery})$ ($r = 0.39$).

Early gait speed averaged 15.4 cycles/minute and late gait speed averaged 14.0 cycles/minute, an 8.8% decrease ($p = 0.19$) (Table 3, Fig. 3).

Patients younger than 65 years at surgery ($n = 10$) had a 14% decrease ($p = 0.03$) in mean activity rate from the early period to the late period: 2.34 million gait cycles/year to 2.02 million gait cycles/year. Patients 65 years or older at surgery ($n = 4$) had a 28% decrease ($p = 0.04$): 1.29 million gait cycles/year to 0.94 million gait cycles/year (Table 4). Patients 65 years or older were less active than patients younger than 65 years in both the early (45% less, $p = 0.02$) and late (53% less, $p = 0.01$) periods (Fig. 4). For patients younger than 65 years at surgery, the total number of gait cycles averaged 11.7 million at 5 years and 25.0 million at latest followup. For patients 65 years or older, the total number of gait cycles averaged 6.5 million at 5 years and 12.5 million at latest followup (Table 5). Patients younger than 65 years had a 9.7% decrease ($p = 0.23$) in mean gait speed from the early to the late period: 16.7 cycles/minute to 15.1 cycles/minute. Patients 65 years or older had a 5.5% decrease ($p = 0.29$): 12.0 cycles/minute to 11.4 cycles/minute (Table 4, Fig. 4). Patients 65 years or older had a

26% slower ($p = 0.01$) mean gait speed than patients younger than 65 years.

At minimum 10-year followup, the mean linear penetration rate was 0.037 ± 0.041 mm/year (range, -0.041 to 0.078 mm/year), the mean volumetric wear rate was 14 ± 14.2 mm³/year (range, -11 to 34 mm³/year), and the mean adjusted volumetric wear rate was 7.3 ± 10.0 mm³/million gait cycles (range, -6 to 17 mm³/million gait cycles). The maximum linear penetration was 0.87 mm. The maximum total volumetric wear was 434.9 mm³. From the early period (first 5 years) to the late period (5–13 years), the mean linear penetration rate decreased ($p = 0.18$) by 42%: 0.043 mm/year to 0.025 mm/year. The mean volumetric wear rate decreased ($p = 0.28$) by 40%: 15 mm³/year to 9 mm³/year. The mean adjusted volumetric wear rate

Fig. 3A–B (A) Activity decreased by 16% ($p = 0.006$) from the early to the late period: 2.04 million gait cycles/year to 1.71 million gait cycles/year. (B) Gait speed decreased by 8.8% ($p = 0.19$) from the early to the late period: 15.4 cycles/minute to 14.0 cycles/minute.

Table 3. Early versus late activity and gait speed

Variable	Early period (first 5 years)	Late period (> 10 years)	p value
Activity (million gait cycles/year)	2.04 ± 0.92 (0.76–3.91)	1.71 ± 0.87 (0.27–2.94)	0.006
Gait speed (cycles/minute)	15.4 ± 6.3 (6.9–32.2)	14.0 ± 4.4 (7.1–22.2)	0.19

Values are expressed as mean ± SD, with range in parentheses.

Table 4. Age-related differences in activity and gait speed

Variable/Age	Early period (first 5 years)	Late period (> 10 years)	% decrease	p value
Activity (million gait cycles/year)				
< 65 years at surgery (n = 10)	2.34 ± 0.90 (0.82–3.91)	2.02 ± 0.79 (0.56–2.94)	14	0.03
≥ 65 years at surgery (n = 4)	1.29 ± 0.37 (0.76–1.56)	0.94 ± 0.57 (0.27–1.57)	28	0.04
Gait speed (cycles/minute)				
< 65 years at surgery (n = 10)	16.7 ± 6.8 (9.5–32.2)	15.1 ± 4.5 (9.4–22.3)	9.7	0.22
≥ 65 years at surgery (n = 4)	12.0 ± 4.0 (7.0–16.4)	11.4 ± 3.3 (7.1–14.5)	5.5	0.29

Values are expressed as mean ± SD, with range in parentheses.

Fig. 4A–B (A) Patients 65 years or older were less active than patients younger than 65 years in both the early (45% less, $p = 0.02$) and late (53% less, $p = 0.01$) periods. (B) Patients 65 years or older tended to have a slower mean gait speed than patients younger than 65 years in both the early and late periods ($p = 0.11$ and 0.08 , respectively). It appeared gait speed declined first and then total number of gait cycles declined later in life.

decreased ($p = 0.38$) by 11%: $6.5 \text{ mm}^3/\text{million gait cycles}$ to $5.8 \text{ mm}^3/\text{million gait cycles}$ (Table 6, Fig. 5). There was a correlation between individual early and late linear penetration rates ($r = 0.64$, $p = 0.006$) and between individual early and late volumetric wear rates ($r = 0.62$, $p = 0.009$).

Discussion

While laboratory wear testing is necessary and valuable [9, 10], the final examination for any bearing is clinical use over time. Although time in situ is a convenient, often-used substitute for the amount of use, in the clinical evaluation of a bearing, it is especially valuable to know how much use. We therefore asked: (1) How does individual patient activity (measured as gait cycles) change with time? (2) How does gait speed change with time? (3) Are there age-related differences in activity and gait speed? And (4) do aging-related changes in activity influence polyethylene wear? We addressed these questions utilizing unique quantitative patient activity data and radiographic wear data collected over 13 years.

The limitations of this study include the following. First, we had only 14 patients with SAM activity data at two time periods over a minimum of 10 years. The challenges in acquiring quantitative activity data are patient compliance in the daily use of the SAM and having dedicated research personnel to work directly with patients during the activity assessments. This explains, at least in part, the paucity of reports that include quantitative activity data. Nevertheless, these 14 patients are representative of the patient with modern joint arthroplasty who can challenge the wear resistance of a bearing. They all were healthy, Charnley Class A, with a relatively low mean age of 55 years and a broad range of ages (26–78 years). Because of the small number of patients and the heterogeneous nature of this sample, a multivariate analysis to control for potentially confounding variables and identify independent predictors was not possible. Second, the sensitivity of the digital radiographic analysis method limits comparisons between the early and late wear periods for individual patients. Third, there was only one type of crosslinked polyethylene analyzed (Marathon®), and our results may not translate to other crosslinked polyethylenes. Another limitation is that the total number of gait cycles is an extrapolation from the two activity sampling periods, which may be either more or less than the actual number of accumulated cycles. These patients were all healthy, and we are unaware of anything

Table 5. Age-related differences in total number of gait cycles

Time	Total number of gait cycles (million gait cycles)		p value
	< 65 years at surgery (n = 10)	≥ 65 years at surgery (n = 4)	
5 years postoperatively	11.7 ± 4.5 (4.1–19.6)	6.5 ± 1.8 (3.8–7.8)	0.005
Latest followup (mean, 11.4 years)	25.0 ± 9.3 (8.4–37.0)	12.5 ± 5.5 (5.8–18.4)	0.006

Values are expressed as mean ± SD, with range in parentheses.

Table 6. Early versus late wear rates

Wear rate	Early period (first 5 years)	Late period (5–13 years)	% decrease	p value
Linear wear rate (mm/year)	0.043 ± 0.036 (–0.005 to 0.111)	0.025 ± 0.066 (–0.086 to 0.115)	42	0.18
Volumetric wear rate (mm ³ /year)	15.0 ± 25.9 (–16.8 to 82.3)	9.0 ± 22.2 (–20.9 to 54.4)	40	0.28
Adjusted volumetric wear rate (mm ³ /million gait cycles)	6.5 ± 18.6 (–7 to 35)	5.8 ± 18.4 (–12 to 33)	11	0.38

Values are expressed as mean ± SD, with range in parentheses.

Fig. 5A–C From the early period (first 5 years) to the late period (5–13 years), (A) mean linear penetration rate decreased by 42%: 0.043 mm/year to 0.025 mm/year; (B) mean volumetric wear rate

decreased by 40%: 15 mm³/year to 9 mm³/year; and (C) mean adjusted volumetric wear rate decreased by 11%: 6.5 mm³/million gait cycles to 5.8 mm³/million gait cycles.

that would contradict the activity extrapolations. The issue of activity sampling has been previously investigated. In a study of 131 patients with total joint arthroplasty, the total number of sampling days for each subject ranged from 7 to 123 days. Random samples of four consecutive measurements were compared to the total days of observation/subject (7–123 days). The gait activity measured over 4 days was correlated to that of the longer sampling period ($r^2 = 0.945$), with no difference in the activity assessment for a sampling of 4 versus 7 days or more [14]. On this basis, our minimum sampling of 5 days is likely to be representative of patient activity over a longer time. Further, we found individual activity in the early and late sampling periods to be correlated.

Individual patient activity generally decreases with aging. In a cross-sectional cohort study, age was associated ($p = 0.048$) with activity [12]. On average, patients who were younger than 60 years walked 30% more ($p = 0.023$) than those who were 60 years or older. There was a high

degree of variability, with a 45-fold difference between the least and most active patients studied. The linear regression analysis from that study predicts a 9.8% decrease in activity over the 11.4 years of observation in the current study. The actual decrease in mean patient activity we observed was 16.2%, suggesting the decrease in patient activity with aging is nonlinear.

Gait speed generally decreases with time. Early gait speed averaged 15.4 cycles/minute and late gait speed averaged 14.0 cycles/minute, an 8.8% decrease. With the numbers available, this difference is not statistically different ($p = 0.19$). We are unaware of any other such studies of gait speed over time in patients with THA. Based on our observations, as patients age, gait speed tends to slow down first, and then the number of gait cycles decreases.

The combination of an 8.8% decrease in walking speed and a 16% reduction in the number of gait cycles over the decade of observation was associated with a 40% decrease in polyethylene wear rate. The highest activity and the

highest wear both occurred during the first 5 years, and both decreased over the next 5 to 8 years. These data have implications for the longer-term performance of hips with crosslinked polyethylene bearings. The first 5 years were predictive of subsequent wear. There was a correlation between individual early (first 5 years) and late (5–13 years) linear penetration rates and between individual early and late volumetric wear rates.

A unique aspect of our analysis was the reporting of an adjusted wear rate: the wear/million gait cycles of a 70-kg patient weight. More commonly used variables, such as sex, age, diagnosis, BMI, and Charnley class, are actually surrogates for the fundamental variable: the amount of use of the implant. Our method more directly assesses that fundamental variable. Further, the adjusted wear rate allows for comparison to the results of hip simulator studies [11]. In a preclinical wear simulator test of this 5-Mrad crosslinked polyethylene, the mean wear rate was 5 mm³/million gait cycles [9]. Our average adjusted wear rate was 6.5 mm³/million gait cycles.

In a systematic review of intermediate-term reports, the mean linear penetration of all types of highly crosslinked polyethylenes was 0.042 mm/year, and this wear rate was associated with a low risk of radiographically apparent osteolysis [5]. This pooled average wear rate is nearly identical to our average 5-year linear penetration rate (0.043 mm/year). At a minimum of 10 years, the mean linear penetration rate was 0.037 mm/year, which was consistent with the reduction in patient activity with aging.

In summary, quantitative activity data indicate the number of gait cycles and gait speed both decrease with age. The number of gait cycles decreased an average of 16% over the decade of observation. The average gait speed of patients 65 years or older was 26% slower than that of patients younger than 65 years. The highest activity and highest wear rates occurred in the first 5 years post-operatively. The decrease in activity with aging was associated with a 40% decrease in late polyethylene wear rate. The wear rates observed are associated with a low risk of developing osteolysis.

Acknowledgments The authors acknowledge and thank Dr. John Martell for his assistance with the radiographic wear analysis.

References

1. Bitsch RG, Loidolt T, Heisel C, Ball S, Schmalzried TP. Reduction of osteolysis with use of Marathon cross-linked polyethylene: a concise follow-up, at a minimum of five years, of a previous report. *J Bone Joint Surg Am.* 2008;90:1487–1491.
2. Charnley J. The long-term results of low-friction arthroplasty of the hip performed as a primary intervention. *J Bone Joint Surg Br.* 1972;54:61–76.
3. Clarke IC, Manley MT. How do alternative bearing surfaces influence wear behavior? Implant Wear Symposium 2007: Engineering Work Group. *J Am Acad Orthop Surg.* 2008;16(suppl 1):S86–S93.
4. Dumbleton JH, Manley MT, Edidin AA. A literature review of the association between wear rate and osteolysis in total hip arthroplasty. *J Arthroplasty.* 2002;17:649–661.
5. Kurtz SM, Gawel HA, Patel JD. History and systematic review of wear and osteolysis outcomes for first-generation highly cross-linked polyethylene. *Clin Orthop Relat Res.* 2011;469:2262–2277.
6. Lachiewicz PF, Heckman DS, Soileau ES, Mangla J, Martell JM. Femoral head size and wear of highly cross-linked polyethylene at 5 to 8 years. *Clin Orthop Relat Res.* 2009;467:3290–3296.
7. Leung SB, Egawa H, Stepniewski A, Beykirch S, Engh CA Jr, Engh CA Sr. Incidence and volume of pelvic osteolysis at early follow-up with highly cross-linked and noncross-linked polyethylene. *J Arthroplasty.* 2007;22:134–139.
8. Martell JM, Berdia S. Determination of polyethylene wear in total hip replacements with use of digital radiographs. *J Bone Joint Surg Am.* 1997;79:1635–1641.
9. McKellop H, Shen FW, DiMaio W, Lancaster JG. Wear of gamma-crosslinked polyethylene acetabular cups against roughened femoral balls. *Clin Orthop Relat Res.* 1999;369:73–82.
10. McKellop HA. Laboratory wear testing. In: Callaghan JJ, Rosenberg AG, Rubash H, eds. *The Adult Hip*. Philadelphia, PA: JB Lippincott; 1998.
11. Schmalzried TP, Shepherd EF, Dorey FJ, Jackson WO, dela Rosa M, Favae F, McKellop HA, McClung CD, Martell J, Moreland JR, Amstutz HC. Wear is a function of use, not time. *Clin Orthop Relat Res.* 2000;381:36–46.
12. Schmalzried TP, Szuszczewicz ES, Northfield MR, Akizuki KH, Frankel RE, Belcher G, Amstutz HC. Quantitative assessment of walking activity after total hip or knee replacement. *J Bone Joint Surg Am.* 1998;80:54–59.
13. Shepherd EF, Toloza E, McClung CD, Schmalzried TP. Step activity monitor (SAM): increased accuracy in quantifying ambulatory activity. *J Orthop Res.* 1999;17:703–708.
14. Silva M, McClung CD, dela Rosa MA, Dorey FJ, Schmalzried TP. Activity sampling in the assessment of patients with total joint arthroplasty. *J Arthroplasty.* 2005;20:487–491.
15. Silva M, Shepherd EF, Jackson WO, Dorey FJ, Schmalzried TP. Average patient walking activity approaches 2 million cycles per year: pedometers under-record walking activity. *J Arthroplasty.* 2002;17:693–697.