Total Hip Arthroplasty Performed for Coxarthrosis Preserves Long-Term Physical Function: A 40-Year Experience

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Abstract *Background:* Measures of long-term success of total hip arthroplasty (THA) over the past 50 years have focused primarily on implant survival, with less evidence on long-term functional outcomes. *Questions/Purposes:* We aimed to study 20-to-40-year functional outcomes after primary THA. We investigated the extent to which (1) functional outcomes after THA are maintained long term; (2) patient characteristics such as age, hip disease diagnosis, and comorbidities affect recovery of function and survivorship after THA; and (3) patients' overall function after THA is affected by the need for revision, the aging process, and associated comorbidities. *Methods:* We retrospectively reviewed outcomes of the senior author's patients between 1968 and 1993. Of 1207 patients, we identified 167 patients (99 female, 68 male; 276 primary THAs) who were at least 65 years old at follow-up and had at least 20 years of follow-up. Mean age at surgery was 55 years; mean follow-up time was 27 years. Bilateral THAs were performed in 109 patients (65%), and revisions in 81 patients (48.5%). Clinical outcomes including pain level, walking ability, range of

motion, and overall function were determined by the Hospital for Special Surgery (HSS) hip scoring system. Contralateral and revision surgery, as well as patient age, sex, and body mass index, were included as covariates. To account for unequally spaced follow-up time points and competing causes of functional decline (e.g., age, contralateral hip disease, and need for revision THA), a latent class mixed model approach was used to identify unobserved classes of patients who had similar outcomes. Linear, quadratic, and piecewise-polynomial growth models were considered for class identification. The best fitting model was determined based on Bayesian information criterion. *Results:* A four-class model of this patient population was identified: (1) the Elderly Class, who had a mean age of 62 years at the time of primary THA; (2) the Bilateral Class, who underwent simultaneous or staged bilateral THA; (3) the Revision Class, who required at least one revision; and (4) the Youngest Class, who had a mean age of 49 years. After an initial period of improvement in all groups, the functional trajectory diverged according to classifications. Age was the strongest determinant of long-term outcome, with HSS hip scores in the Elderly Class declining after about 20 years. The Youngest Class maintained good-to-excellent hip function for over 30 years. Revision THA and contralateral THA accounted for a temporary decline in function, after which overall good function was regained for the long term. *Conclusions:* All classes in the study population enjoyed good-to-excellent outcomes after THA for about 20 years. Thereafter, functional decline was attributed more to aging than to the need for revision. One or more revision THA did not negatively influence long-term clinical outcomes, suggesting that, even for younger patients, symptoms, rather than the avoidance of possible revision, should be the primary determining factor when indicating THA.

Level of Evidence: Level IV: Retrospective therapeutic study

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Introduction

The success of modern total hip arthroplasty (THA) to manage end-stage degenerative hip conditions has been well documented since the procedure was introduced over 50 years ago. During those 5 decades, major advances in prosthetic design, surgical technique, and clinical care have reduced the occurrence of complications such as infection, prosthetic dislocation, fatal pulmonary embolism, and loss of prosthetic fixation [11, 12, 33, 34]. Surgeons performing THA have witnessed the benefits gained from these advances and have documented improvements in function and pain relief for at least 15 years [5, 7, 10, 19, 29, 34, 40]. Most intermediate and long-term studies, however, focus on implant survival and provide little clinical evidence of function, mobility, and pain levels over a lifetime in patients who have undergone THA.

Early instruments designed to evaluate patient-based functional outcomes included assessments of hip pain, range of motion (ROM), muscle strength, and walking. The Merle D'Aubigné scale, the Hospital for Special Surgery (HSS) hip scoring system, and the Harris Hip Score are examples of such assessments [18, 28, 36, 40]. Currently, patient-reported outcome measures (PROMs) including the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), the 36-item Short Form Health Survey (SF-36), and the EuroQol are included in registry data, but follow-up times are short. Although the earlier instruments developed to record functional assessments were not patient reported, if recorded consistently over a patient's lifetime they can provide a reasonable assessment of hip functionality and quality of life.

Three institutions have reported valuable evidence of THA performance beyond 25 years [5, 7, 42]. These reports focus on the longevity or survivorship of the hip implant until revision or patient death. Reported clinical results are limited to WOMAC scores collected from the surviving patients at final follow-up [6]. While these reports are useful for providing guidance on the longevity and durability of implant designs, they lack information on the effects on long-term outcomes of revision and patient aging. To date, long-term studies reporting PROMs after THA are not available [33], making it difficult for surgeons to inform younger patients in need of THA of reasonable expectations for their future.

We sought to determine 40-year clinical outcomes of patients who underwent THA by a single surgeon, including those who had revision surgeries. Specifically, we assessed the extent to which (1) functional outcomes after THA surgery, as assessed by HSS hip score, are maintained long term; (2) patient characteristics such as demographics, hip disease diagnosis, and comorbidities affect recovery of function and survivorship following THA; and (3) THA patients' overall function is influenced by revision, the aging process, and comorbidities.

Methods

After institutional review board approval was obtained, the cohort for this retrospective study was identified through review of case records of 1207 patients on whom the senior

author (PDW) performed primary THA between 1968 and 1993. Patients were included if they (1) underwent primary THA as the index surgery and (2) had a minimum of 20-year follow-up. The focus of this study was long-term follow-up; patients with shorter follow-up were therefore excluded.

One-hundred sixty-seven patients met these inclusion criteria. Their ages at the time of index surgery ranged from 25 to 74 years (median, 55 years) and at the time of the last recorded follow-up from 66 to 100 years (median, 82 years). At follow-up the youngest patient was 70 years old and the oldest was 99 years old. At the time of the last recorded follow-up, 93 patients were still living, 73 were deceased, and one patient was lost to follow-up 28 years after event surgery. The median time from event surgery to revision or last follow-up if no revision was required was 21.6 years (Table 1). Ninety-nine patients (69%) were female. At the time of the index surgery, the median body mass index (BMI) was 25, ranging from 18.5 to 31.8. The patient population was healthy with few medical comorbidities, with 62% categorized as American Society of Anesthesiologists (ASA) class I, 35% as ASA class II, and 4% as ASA class III. Osteoarthritis was the predominant diagnosis, occurring in 88% of the patients. Post-traumatic arthrosis, developmental dysplasia of the hip, and osteonecrosis were the most common etiologies of secondary osteoarthritis (Table 2).

The criteria of age and length of follow-up were applied to capture the functional outcomes of patients as they aged, and the criteria were not mutually exclusive. Any patient who had reached the age of 65 or older at 20-year (or more) follow-up was included in the study, regardless of their age at time of event surgery.

The HSS hip score [40] was used to assess the clinical performance of patients who had undergone THA (Table 3). The degree of patients' pain ("Pain"), walking capability and endurance ("Walking"), muscle power and ROM ("Motion"), and functional level ("Function") were assessed at the time of face-to-face clinical visits or from submitted self-assessment hip replacement questionnaires. A numeric rating ranging from 0 (worst) to 10 (best) was assigned and recorded on individual patients' hip worksheets at the time of each follow-up. The scores for the four domains—Pain, Motion, Walking, Function—were summed together. A score of 35 to 40 was considered excellent, 30 to 35 good, 25 to 30 fair, and less than 25 poor. The total ratings from individual patients' hip worksheets were captured in scoring periods that ranged from 3 weeks to 44 years after index surgery. If a rating was missing for any of the four domains at the time of follow-up, the entire scoring period was ignored. If the patient was seen or treated in follow-up by another surgeon, that event date was recorded as a follow-up, but no scores were assigned to that event.

All subsequent revision THAs and/or contralateral THAs performed by surgeons other than the senior author were documented and included as part of the long-term follow-up.

Statistical Analysis

We applied a non-linear latent class mixed model on the ordinal longitudinal HSS scores and a proportional hazard

Table 1 Total study population ($n = 167$)

Age at time of surgery	Youngest: 25 years	Oldest: 74 years	Mean: 55.05 years
Body mass index, pre-operative	Maximum: 25.12	Minimum: 25	Mean: 25.12
Total years of follow-up	Shortest: 19.6 years	Longest: 45 years	Median: 25 years
Time to revision or last follow-up (if no revision)	Shortest: 0.6 months	Longest: 45 years	Median: 21.6 years
Sex			
Male			$n = 68$ 40.7%
Female			$n = 99$ 59.3%
Pre-operative diagnoses			
1. OA (osteoarthritis)			$n = 147$ 88%
2. Ankylosis/deformity			$n = 7$ 4.1%
3. Failed hemiarthroplasty (cup/femur)			$n = 5$ 2.9%
4. RA (rheumatoid arthritis)			$n = 3$ 1.8%
5. All others (osteonecrosis, congenital degeneration of the hip, fracture of femur, etc.)			$n = 5$ 2.9%
ASA Class designation, pre-operative			
ASA Class I			$n = 103$ 61.7%
ASA Class II			$n = 59$ 35.3%
ASA Class III			$n = 5$ 3%
ASA Class IV			$n = 0$ 0%

ASA American Society of Anesthesiologists

model for time-to-revision to the study population [22]. Changes in the HSS hip scores over time and time-to-revision were linked through unobserved latent classes, which account for heterogeneity and represent patients with different trajectories of HSS scores and risks of revision.

Unlike traditional analysis, in which longitudinal and time-to-event outcomes are conducted separately, neglecting the association between the two outcomes, the joint model accounts for the association between the longitudinal and the time-to-event outcomes with shared random effects [43]. The joint model has received considerable attention in the past two decades and has been shown to provide accurate, efficient, and robust estimations [21, 42].

Unlike the linear mixed effect model, which estimates a single trajectory for an entire population, the latent class mixed model combines a mixed model to account for the individual correlation in repeated measures and a latent class model to discriminate homogeneous latent class groups when modeling trajectories [13, 23, 43]. Due to the ceiling and floor effects of the ordinal HSS hip scores, a non-linear mixed model was used.

Similarly, the latent survival model of the joint modeling is a class-specific proportional hazard model. Revision THA was used as an end point because it has been the accepted benchmark for longitudinal studies [5, 7, 9, 28, 40].

The latent class group is described using a multinomial logistic model. We included age, BMI, sex, and baseline diagnosis of osteoarthritis, all recorded pre-operatively at time of event surgery, and an indicator for contralateral bilateral surgery as covariates.

A joint model was specified for each latent class. The trajectory of HSS scores for each latent class was estimated as a function of time. In each latent class, the longitudinal HSS score is explained according to a linear and a quadratic term of follow-up time (in years) since the first primary THA (event surgery) at the population level (fixed effect), accounting for non-linear change in HSS hip score over time. Random effects were included to account for the variability among

patients in the intercept and both linear and quadratic slopes of change in score over time. The observed longitudinal outcomes were linked to the process model through a non-linear link model. A spline link function with six nodes at quantiles was specified.

Survivorship analysis was used to assess time to revision and was calculated from the date of event surgery for each patient until the date of censoring due to revision or the last follow-up. We assumed that the time to revision in each latent class could be described by a Weibull proportional hazard model [22], with class-specific baseline hazard function. In addition, an indicator for contralateral surgery was included as a time-dependent covariate.

To choose the appropriate number of latent classes, a series of latent class models with varying class size starting from 1 were calculated. The optimal number of latent classes was determined by comparing the Bayesian information criterion (BIC) [32]. We chose the number of latent classes with the smallest BIC.

Data were analyzed using SAS for Windows 9.3 [30] and R package lcmm developed by Proust-Lima et al. [24, 25].

Results

A total of 167 patients who had undergone 276 THAs were included: 58 patients underwent unilateral THA, 43 patients underwent simultaneous bilateral THA, and 66 patients underwent staged bilateral THA with the contralateral procedure occurring at least a year after the first. Of the 1040 patients not included in the study, 906 were deceased, 98 lacked 20-year follow-up, 21 had not reached the age of 65 years at the time of last recorded follow-up, and 15 resided in other countries and states and did not return for follow-up. The implant models used varied and reflected changes in available technology from the first case (1968) to the last (1993). For fixation, 142 THAs had cemented components, 53 were

Table 2 Osteoarthritis (OA) secondary to underlying causes

	Class 1/Elderly (<i>n</i> = 34)		Class 2/Bilateral (<i>n</i> = 35)		Class 3/Revision (<i>n</i> = 57)		Class 4/Youngest (<i>n</i> = 41)		All (<i>n</i> = 167)	
	<i>n</i>	% cohort	<i>n</i>	% cohort	<i>n</i>	% cohort	<i>n</i>	% cohort	<i>n</i>	% total study population
OA as primary diagnosis	32	94.1	32	91.6	51	89.4	32	78	147	88
OA secondary to underlying causes									<i>N</i>	% Cohort
Trauma	2	5.8			1	1.75	4	9.7	7	4.1
Congenital degeneration of the hip	4	11.7			10	17.5	7	17	24	14.3
Slipped capital femoral epiphysis	1	2.9	3	8.5	3	5.2	3	7.3	10	6
Osteonecrosis	2	5.8	3	8.5	6	10.5	3	7.3	11	6.6
Protrusion deformity	1	2.9			1	1.75			2	1.2
Ankylosis and deformity	1	2.9			1	1.75			4	2.4
Hip dysplasia			2	5.7	1	1.75			2	1.2
Hematomacrosis			1	2.8	1	1.75			1	0.6
Acromegaly									1	0.6
Legg-Perthes			1	2.8	1	1.75			1	0.6
Gaucher's disease							1	2.4	1	0.6
Juvenile rheumatoid arthritis							1	2.4	1	0.6
Pseudoachondroplasia							1	2.4	1	0.6
Proliferative synovitis							1	2.4	1	0.6
Deformity from childhood hip infection							1	2.4	1	0.6
Totals: OA secondary to underlying causes for each class	11	32.3	10	28.5	25	43.8	22	53.6	68	40.6

uncemented acetabular cups with cemented femoral component (hybrid), and 72 were uncemented; for bearings, 52 were ceramic-on-polyethylene bearings, and the remainder were cobalt-chrome-on-polyethylene bearings (Tables 4 and 5).

Complications after the primary THA were uncommon, occurring in just 13 patients (5%). Five patients experienced non-fatal venous thromboembolism (VTE), two suffered pneumonia, two had wound complications attributed to post-operative hematoma, one experienced a temporary aphasia, and two had non-fatal cardiac complications including one myocardial infarction and one case of rapid atrial fibrillation. One revision was required for 81 (49%) patients, and in total 101 hips were revised. Median time from event surgery to first revision was 13 years. Loosened/subsided/migrated components, of the cup or femoral stem or both, was the predominant diagnosis necessitating revision in 81.5% of the patients. Other reasons for revision were fracture of the femur, stem, or socket (10%); infection (1%); and dislocation (5%).

Eighteen patients experienced peri-operative complications as a result of revision surgeries. Five patients had extensive blood loss requiring transfusion. Four patients had cardiac complications, including two with non-fatal myocardial infarctions and two with arrhythmias requiring treatment. Four patients experienced recurrent dislocations leading to additional revision, and four patients had symptomatic leg length discrepancy. One patient suffered sciatic nerve palsy.

These patients had varying baseline characteristics that predicted long-term function and survivorship of the THA. By applying the statistical model previously described, we tracked the functional trajectory of this heterogeneous population. Four latent classes were identified by the analysis. The median pre-operative HSS hip score for all patients was 21, indicating poor hip function, with no difference among the four classes. The overall functional trajectory of the four classes improved post-operatively, and then diverged according to the classifications (Fig. 1).

Class 1: Elderly Class

The prominent characteristic that emerged in the cohort identified as Class 1 was that of relatively advanced age. This class consisted of 34 patients whose mean age at the time of event surgery was 62 years; median age at last recorded follow-up was 86. A majority of this class (*n* = 27, 79%) was female, and 59% (*n* = 20) of the patients were deceased when the study concluded (Table 5). The Elderly Class showed the greatest change in functional outcome over time. Initially, this class reported the highest outcome scores, but after approximately 20 years the scores declined steeply, dropping to poor functionality (HSS hip score lower than 25) by 30 years from event surgery (Fig. 1). This decline corresponds to the aging process.

Table 3 Hospital for Special Surgery (HSS) hip rating system

Ratings	0–1	2–3	4–5	6–7	8–9	10
Pain	All the time. Unbearable. Strong medication frequently	All the time but bearable. Strong medication occasionally. Salicylates frequently	None or little at rest. With activities. Salicylates frequently	When starting, then better, or after a certain activity. Salicylates occasional	Occasional and slight	No pain
Muscle power (MP) and motion ^a	Ankylosis with deformity	Ankylosis with good functional position	MP—poor to fair. Arc of flexion less than 60°. Restricted lateral and rotary movement	MP—fair to good. Arc of flexion up to 90°. Fair ^b lateral and rotary movement	MP—good or normal. Arc of flexion over 90°. Good ^c lateral and rotary movement	MP—normal. Motion—normal or almost normal
Walking	Bedridden	Wheelchair. Transfer activities with walker	Markedly restricted. No support—housebound or one support—less than one block or bilateral support—less than three blocks	Moderately restricted. No support—less than one block or one support—up to five blocks or bilateral support—unrestricted	Mildly restricted. No support—limp. One support—no limp	Unrestricted. No support or appreciable limp
Function	Completely dependent and confined	Partially dependent	Independent. Limited housework, shops	Most housework, shops freely, desk-type work	Very little restriction. Can work on feet	Normal activities

^a Precedence in rating was given to active movement, but usually both active and passive movement were the same

^b Fair lateral movement: 10° abduction, 10° adduction. Fair rotatory movement: internal rotation 10°, external rotation 20°

^c Good lateral movement: 20° abduction, 20° adduction. Good rotatory movement: internal rotation 20°, external rotation 40°

Osteoarthritis was the described pathology in 94% of the cases, and it was the underlying cause in 32% of these cases (Table 2). Seventeen percent of the patients required revision.

Class 2: Bilateral Class

The most common characteristic of this class ($n = 35$) was that 74% of the patients had bilateral disease requiring either simultaneous bilateral THA under one anesthesia or contralateral THA (one THA followed by another on the opposite side one or more years later) (Table 5). The functional trajectory of the Bilateral Class showed an immediate improvement in HSS hip scores post-operatively, followed by a sloping decline 10 to 15 years later. After 16 years from event surgery, there was a strong bounce back of functional improvement into the excellent range that was well maintained into 40 years of follow-up (Fig. 1). This was the only class in which scores had not declined 40 years later. The temporary decline in function corresponded to the need for contralateral surgery, with a mean time between sides of 12 years. The mean time between event surgery and first revision surgery for this class was 17 years, the point after which good-to-excellent function was maintained. At the time of the event surgery, mean age for this cohort was 58 years; the youngest was 33 and the eldest 67 years. A majority of this class (63%) was male. At study conclusion, the mean age was 83 years and 51% of patients were deceased. Eighty-eight percent of the class was diagnosed with osteoarthritis, and 31% had diagnoses of secondary osteoarthritis (Table 2); 45% of the patients required revision (Table 5).

Class 3: Revision Class

This cohort required the highest number of revision THAs, at 98% ($n = 56$) of its members. The mean time from event surgery to first revision was 11 years. The Revision Class achieved initial improvement in the mean function scores to the excellent range and maintained in the good range for 18 years, despite the high percentage requiring revision surgery. At about 25 years past the date of event surgery scores in this class began to decline into the good-to-fair range (Fig. 1). The median age for this cohort was 53 years, the youngest 36 and the eldest 69 years. Just over half of this class (56%) was female. By the end of the study the mean age was 81 years and 44% of patients were deceased. Ninety-one percent had osteoarthritis as the primary diagnosis, with 44% of those diagnosed with secondary osteoarthritis (Tables 2 and 5).

Class 4: Youngest Class

The youngest group of patients at time of event surgery fell into the fourth class ($n = 41$). At the time of event surgery, the median age of the Youngest Class was 49 years, the youngest 25 and the eldest 64 years. The Youngest Class had improved scores that were well maintained for 25 years. Between 30 and 40 years past the date of event surgery there was a gradual downward sloping of scores, although even at

Table 4 Implant types and fixation

Implant		Bearing	Fixation	Number
CAD Muller			Cemented	6
Muller			Cemented	2
McKee/Farrar			Cemented	7
Charnley			Cemented	31
TR28			Cemented	2
T28			Cemented	6
Harris/Galante			Uncemented	16
Anthropometric total hip (ATH)		Ceramic	Uncemented	32
Ranawat/Burstein			Cemented, uncemented, hybrid	1 each = 3
Each component/different model				
Femoral component	Socket component	Bearing	Fixation	Number
8311	ATH	Ceramic	Uncemented	10
8311	ATH	Cobalt/chrome	Uncemented	3
8311	Harris/Galante		Uncemented	1
8311	Ranawat/Burstein	Ceramic	Uncemented	1
8911	ATH	Ceramic	Hybrid	7
8911	ATH	Cobalt/chrome	Hybrid	4
8911	Harris/Galante		Hybrid	4
8911	Ranawat/Burstein		Hybrid	4
DF-80	Charnley		Cemented	13
DF-80	T-28		Cemented	7
DF-80	Triad		Cemented	2
T-28	Standard high-density polyethylene (HDP)		Cemented	19
TR-28	Standard HDP		Cemented	9
TriAD	Tibac		Cemented	18
TriAD	Charnley		Cemented	2
TriAD	Standard HDP		Cemented	4
TriAD	Harris/Galante		Hybrids	19
TriAD	ATH		Hybrids	6
CUSTOM	Charnley		Cemented	2
CUSTOM	Standard HDP		Cemented	3
CUSTOM	TIBAC		Cemented	4
Ranawat/Burstein	Triology		Hybrid and uncemented	1 each = 2
CAD Muller	Standard HDP		Cemented	1
Charnley	Standard HDP		Cemented	1
Osteonics	Harris/Galante		Hybrid and uncemented	1 each = 2
Osteonics	Trilogy		Cemented	1
Osteonics	ATH		Hybrid	1
Osteonics	Dulac		Uncemented	1
VerSys Heritage			Hybrid	5
VerSys Heritage		Ceramic	Uncemented	1
VerSys Fiber Metal			Uncemented	2
Anatomic (A-2)			Cemented	1
Secure-Fit		Ceramic	Uncemented	1
Bias			Uncemented	1

^a No implant types for $n = 9$ contralateral procedures performed by outside surgeons

40 years past the date of event surgery, functional scores continued to remain in the good range (above 30) (Fig. 1).

Sixty-six percent of this class was female, and 34% male. At the conclusion of the study the mean age was 78 years, none of the patients had died, and one patient was lost to follow-up. Fifty-four percent of the patients were diagnosed with secondary osteoarthritis with associated etiologies (Table 3). Seven percent of this class ($n = 3$) required revisions (Table 5).

Discussion

The purpose of this study was to describe the 20-to-40-year functional outcomes in patients who had undergone THA

performed by a single surgeon. We also sought to determine how heterogeneity in patient characteristics may predict long-term outcome following THA. The results indicate that most patients enjoyed excellent outcomes for about 20 years. We characterized longer-term outcomes into four classes with distinct trajectories defined by age at index THA, presence of bilateral hip disease, or revision requirement. The Elderly Class (mean age, 62 years), defined by most advanced age at the time of index THA, had the greatest initial benefit but the sharpest eventual decline, which began at about 20 years after THA. The Bilateral Class, most of whom underwent simultaneous or staged bilateral THA for bilateral hip disease, had the most enduring excellent outcomes, with only a slight, temporary decrease in HSS hip score at about 12 years, the mean time to contralateral

surgery. The Revision Class maintained excellent outcomes for about 25 years, before a gradual decline, despite a high rate (98%) of at least one revision. The Youngest Class (mean age, 49 years at index THA) maintained excellent outcomes for the longest duration, but their HSS hip scores also began to decline at 30 to 40 years.

Several limitations stem from our study design. This is a retrospective review of a selected group of patients from a single surgeon's practice. While the full registry of his THA cases was quite extensive (1207 patients), the available cohort was a small proportion (167 patients). This was unavoidable, given the long duration of follow-up, but it may have skewed the results if we unwittingly selected for patients with specific outcomes based on their long-term loyalty to the surgeon. Some data from records was missing; we cannot know how the analyses were affected by missing data. Despite this, we noted significant heterogeneity in our patient population, ensuring at least some measure of generalizability of our findings. Also, over the years the surgeon used a variety of prosthetic types. In the early years, the cemented Charnley prosthesis was his standard, but with the advent of hybrid and uncemented designs his preferences changed. While this introduced variability in our study, the surgeon's implant choices were necessitated by his adoption of the best available technologies. Another limitation was the use of the calculated HSS hip score. It was developed by the senior author [40] and applied throughout the long period of follow-up. Intra-observer reliability cannot be assessed, but this surgeon consistently used the score over his career. The HSS hip score is not a patient-reported outcome and is therefore not an optimal instrument to measure overall quality of life. It does, however, summarize hip function and the patient's ability to perform typical activities of daily living and can reflect the patient's overall well-being. It has not been assessed as a function of age, and so our conclusion that HSS hip score decreases after age 80 may be challenged in future studies. The observation that it degrades with advancing age lends support to the assumption that it is a crude but useful assessment of activity and independence. Some studies report that simple assessments as opposed to detailed PROMs may often provide similar conclusions [45]. Our observations support the continued use of PROMs for future long-term studies.

Previous studies have reported mixed findings of the effect of advanced age on THA outcomes [14]. Our findings are consistent with other long-term studies examining the relationship between aging and implant function but add clarifying and clinically relevant details.

We observed that in the intermediate term (up to 20 years), outcomes in the Elderly Class are similar to those found in other age groups. That the ensuing decline is related to the aging process per se is supported by our observation that decreasing hip scores are also observed in other classes, as well, as patients approach their 80s. Hip scores in the Youngest Class declined after 30 to 40 years and in the Revision Class after about 25 years. This suggests that, regardless of the age at index THA and time since index THA or occurrence of revision, the aging process may be the

most important factor affecting clinical outcome in patients 80 years and older.

Our findings also shed new light on the long-term outcomes after revision THA. The overall revision rate for the study population was 49%, which is somewhat high but consistent with previous reports in similar cohorts. Among 262 patients (330 hips) undergoing primary THA by a single surgeon between 1970 and 1972, the revision rate in the 34 patients available for follow-up at 30 years was 32% [7]. In a much larger cohort (22,066 hips in 17,409 patients) undergoing primary THA at a single institution between 1962 and 2005, survival, with revision for any reason as the endpoint, was 30% at 31 years [42]. Our overall cohort was relatively young, with a mean age of 55 years at index THA. An older cohort would be expected to have lower revision rates. Also, our series includes THA technology that was available up to 1993; more recent innovations would likely provide better survivorship for today's THA candidate.

More important, our study demonstrates that THA provides a significant improvement in hip function and presumably quality of life that will be maintained until advanced age even when revision surgery is required. Revision THA poses high levels of risk to patients, and short-term follow-up in many cases is associated with a loss of hip function in spite of a successful re-implantation of new THA components [1, 6, 16, 17, 27]. However, our findings indicate that, over the long-term, patients who have undergone successful revision have restored function and quality of life. This is consistent with a previous study of clinical outcomes in a large cohort (1176 patients) of revision THA patients, reporting moderate Oxford hip scores and 92% of patients satisfied 10 years after revision [20]. The goal for THA is to provide excellent hip function without need for revision, but our analyses show that when expertly performed, revision can restore the patient to a level of function commensurate with the goals of the primary surgery [3, 9, 12, 19, 20, 27, 39].

Taken together, our findings on the effects of age and revision on long-term THA outcomes has important implications for counseling patients on the timing of THA. Younger patients with damaged or diseased hips who have no comparable alternative for relief other than to undergo THA should know that THA can confer long-term function and quality of life that may outweigh the risks involved in revision [10, 28, 30, 31, 38]. Twenty or more years after index THA, the Revision Class, in which 98% of patients underwent at least one revision, had higher HSS hip scores than the Elderly Class, whose mean age at index THA was nearly 10 years older. Conversely, undergoing index THA at a later age conferred no advantage in the long term on HSS hip scores. A recent editorial in *The Lancet* questioned the wisdom of performing THAs in younger patients, citing an article by Bayliss et al., demonstrating high lifetime relative risk of revision (29%) in patients 50 to 54 years at index THA [4, 31]. While many surgeons counsel patients to delay THA because of the higher risk of revision in younger patients, the reality is that more THAs are being performed in younger patients. A National Center for Health Statistics analysis of hospital data on THAs from 2000 to 2010

Number of patients and number of revision THAs	<0.0001									
	82.4	19	54.3	1	1.8	38	92.7	86	51.5	
Patients who had 0 revision THA						2				
Patients who had one revision THA	11.8	11	31.4	26	45.6	2	4.9	43	25.7	
Patients who had two revision THAs	5.9	5	14.3	23	40.4	1	2.4	31	18.6	
Patients who had three revision THAs	0	.	0	5	8.8	.	0	5	3	
Patients who had four revision THAs	0	.	0	2	3.5	.	0	2	1.2	
Total patients who had revision THA	17.7	16	45.7	56	98	3	7	81	48.5	
Number of active/deceased patients										
Patients active	38.2	19	54.3	32	56.1	29	70.7	93	55.7	
Patients deceased	61.8	15	42.8	25	43.9	12	29.3	73	43.7	
Patients lost to follow-up	0	1	4.8	.	0	.	0	1	0.06	

showed that while THAs rose by 92% in people ages 75 and older, they increased by 205% in people ages 45 to 54 years [41]. The 2016 American Joint Registry Report (AJRR) observed a mean age at THA of 66 years, nearly 10 years younger than mean ages reported in two other national cohorts prior to 2010 [8, 15]. Our study supports this trend for younger patients to undergo THA and makes a strong argument for more long-term studies that use PROMs, rather than revision, as the measure of long-term success.

The outcomes of the Bilateral Class indicated that disease in a contralateral hip compromised function until both hips were repaired, at which point patients returned to full function and maintained that improvement long term. That this class maintained excellent hip scores even after 40 years was surprising, given that the mean age at index THA (58 years) was only a few years lower than that of the Elderly Class (62 years). The mean time to contralateral THA was 12 years, indicating that many patients had surgery at 70 years or older. This class may represent a particularly robust sub-population of patients who were healthy enough to undergo bilateral THA at index surgery or a contralateral THA at an even greater age at index surgery than in the Elderly Class.

The patient population we studied is quite heterogeneous, and when patients were grouped into latent classes with similar characteristics, different long-term clinical outcomes of THA were observed. We identified four latent classes in this population with similar baseline characteristics that predicted a particular outcome for that class. Most long-term outcome studies, including those utilizing large registries, report unstratified results for an entire patient population [2, 5, 7, 9, 26, 33, 35, 37]. This study clearly establishes that THA populations are not homogeneous and that the predicted long-term success of a THA should be related to the patient's baseline characteristics. We found differences in age, gender, bilaterally of hip disease, and causes of secondary osteoarthritis to be potentially confounding variables in predicting long-term survival of THA. We suspect that there are perhaps better predictors that were not analyzed here. Our findings suggest that future studies should strive to elucidate more specific baseline patient characteristics related to THA long-term performance than we have presented here, stratifying their analyses according to such characteristics.

In conclusion, we found that a heterogeneous population who underwent THA prior to 1993 enjoyed excellent long-term outcomes with improved hip function that persisted in spite of revision being performed in nearly 50% of the group. The group differences in baseline characteristics could be used to predict survivorship and need for revision. Analyzing long-term clinical outcomes with stratification of patients based on age at index THA, bilateral disease, and need for revision, we showed age, not need for revision, to be the major determinant of long-term clinical outcomes. Our findings suggest that, even for younger patients, symptoms, rather than the avoidance of possible revision, should be the primary factor when determining the need for THA.

Fig. 1. Class comparisons of survivorship and HSS Hip Scores.

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Compliance with Ethical Standards

Conflict of Interest: Philip D. Wilson, Jr., MD, Leslee Wong, BA, Yuo-Yu Lee, PhD, and Stephen Lyman, PhD, declare that they have no conflicts of interest. Charles N. Cornell, MD, reports receiving personal fees as a consultant from Exactech, outside the submitted work. Dr. Cornell recused himself from oversight of the peer review of this article.

Human/Animal Rights: All procedures followed were in accordance with the ethical standards of the responsible committee on human experimentation (institutional and national) and with the Helsinki Declaration of 1975, as revised in 2013.

Informed Consent: Informed consent was waived from all patients included in this study.

Required Author Forms Disclosure forms provided by the authors are available with the online version of this article.

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