Estimating the Burden of Total Knee Replacement in the United States

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Background: In the last decade, the number of total knee replacements performed annually in the United States has doubled, with disproportionate increases among younger adults. While total knee replacement is a highly effective treatment for end-stage knee osteoarthritis, total knee replacement recipients can experience persistent pain and severe complications. We are aware of no current estimates of the prevalence of total knee replacement among adults in the U.S.

Methods: We used the Osteoarthritis Policy Model, a validated computer simulation model of knee osteoarthritis, and data on annual total knee replacement utilization to estimate the prevalence of primary and revision total knee replacement among adults fifty years of age or older in the U.S. We combined these prevalence estimates with U.S. Census data to estimate the number of adults in the U.S. currently living with total knee replacement. The annual incidence of total knee replacement was derived from two longitudinal knee osteoarthritis cohorts and ranged from 1.6% to 11.9% in males and from 2.0% to 10.9% in females.

Results: We estimated that 4.0 million (95% confidence interval [CI]: 3.6 million to 4.4 million) adults in the U.S. currently live with a total knee replacement, representing 4.2% (95% CI: 3.7% to 4.6%) of the population fifty years of age or older. The prevalence was higher among females (4.8%) than among males (3.4%) and increased with age. The lifetime risk of primary total knee replacement from the age of twenty-five years was 7.0% (95% CI: 6.1% to 7.8%) for males and 9.5% (95% CI: 8.5% to 10.5%) for females. Over half of adults in the U.S. diagnosed with knee osteoarthritis will undergo a total knee replacement.

Conclusions: Among older adults in the U.S., total knee replacement is considerably more prevalent than rheumatoid arthritis and nearly as prevalent as congestive heart failure. Nearly 1.5 million of those with a primary total knee replacement are fifty to sixty-nine years old, indicating that a large population is at risk for costly revision surgery as well as possible long-term complications of total knee replacement.

Clinical Relevance: These prevalence estimates will be useful in planning health services specific to the population living with total knee replacement.

Total knee replacement is widely used to relieve pain and improve functional status in patients with symptomatic, end-stage knee osteoarthritis¹⁻³. In the last decade, the

number of primary total knee replacements performed annually in the U.S. doubled, exceeding 620,000 procedures in 2009, with >97% of these performed for a principal diagnosis of knee osteoarthritis^{4,5}.

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Total knee replacement is an effective treatment for end-stage knee osteoarthritis, with symptomatic improvement exceeding 85% and long-term failure rates of <1% per year⁶⁻⁸. However, individuals who undergo total knee replacement are at risk for a variety of complications, such as infection, periprosthetic fracture, symptomatic implant loosening, and implant wear leading to mechanical failure^{9,10}. These complications substantially diminish the benefits of total knee replacement and often necessitate revision surgery¹¹.

Growth in total knee replacement utilization has been disproportionately high among younger individuals (forty-five to sixty-four years old)¹²⁻¹⁴. As a result, the average age at which patients receive total knee replacement has decreased over time⁴. The rapid growth in total knee replacement utilization among younger adults, coupled with increased life expectancy, implies that many more individuals are living with total knee replacement longer than ever before.

Despite a high success rate and relatively low risks of failure and/or complications, as more adults in the U.S. undergo total knee replacement, the population at risk for such complications increases. While the annual utilization of total knee replacement over time has been described^{12,14,15}, estimates of the number of persons in the U.S. living with knee implants have not been reported, to our knowledge. Such estimates would be useful in planning health services specific to the population living with total knee replacement, such as anticipation of revision total knee replacement and management of periprosthetic fractures and infections. We aimed to quantify the burden of total knee replacement in the U.S. by estimating the number of adults currently alive with a primary or revision total knee replacement.

Materials and Methods

Analytic Overview

We used the Osteoarthritis Policy (OAPol) Model, a validated computer simulation model of the natural history and management of symptomatic knee osteoarthritis, combined with data on total knee replacement incidence, to estimate the prevalence of primary and revision total knee replacement among adults in the U.S. and to derive the lifetime risk of primary and revision total knee replacement in the U.S. The annual incidence of total knee replacement among persons with advanced knee osteoarthritis (Kellgren-Lawrence grade 3 or 4) was derived from two multicenter longitudinal studies of persons with knee osteoarthritis (the Multicenter Osteoarthritis Study [MOST] and the Osteoarthritis Initiative [OAI])^{16,17}. We combined estimates of the prevalence of total knee replacement with 2009 U.S. Census data to calculate the number of adults in the U.S. currently living with total knee replacement.

OAPol Model

The OAPol Model is a validated, state transition, computer simulation model of the natural history of knee osteoarthritis^{18,19}. "State transition" implies that the natural history and outcomes of clinical management of knee osteoarthritis are characterized as a series of annual transitions between health states. The model is implemented as a Monte Carlo simulation, meaning that the health-state-to-health-state pathway followed by an individual hypothetical subject is determined by a random-number generator and a set of estimated transition probabilities between states. This simulation is repeated for at least one million individuals to achieve stable estimates.

Health states in the model are defined by knee osteoarthritis severity and the presence or absence of several comorbidities (obesity, coronary heart disease, diabetes mellitus, chronic obstructive pulmonary disease, cancer, and musculo-

skeletal disorders not including osteoarthritis). Death can occur from any health state, although the presence of certain comorbidities (obesity, coronary heart disease, diabetes mellitus, and cancer) increases an individual's risk of mortality. Further details of health states in the OAPol Model are published elsewhere¹⁹.

Model Input Parameters

Baseline Cohort Demographics

We simulated male and female cohorts from the age of twenty-five years until death. We used data from the National Health and Nutrition Examination Survey (NHANES) for 2005 through 2008 for individuals from twenty to twenty-nine years old to estimate the distribution of baseline body mass index (BMI), stratified by sex (Table I)^{20,21}. The OAPol Model simulates changes in BMI with age, according to a model derived from NHANES data that has been previously described¹⁹.

Incidence and Progression of Knee Osteoarthritis

The annual incidence of physician-diagnosed, symptomatic knee osteoarthritis, stratified by age, sex, and obesity, was derived using data from the National Health Interview Survey. These data have been previously presented²². In our model, all incident cases of knee osteoarthritis were considered to be Kellgren-Lawrence grade 2 accompanied by knee pain. Progression from Kellgren-Lawrence grade 2 to grade 3 and, subsequently, Kellgren-Lawrence grade 4 was based on previously published rates of the annual progression of knee osteoarthritis¹⁹.

Nonsurgical Treatment for Knee Osteoarthritis

All individuals who developed symptomatic knee osteoarthritis underwent a sequence of treatment regimens, which were modeled on the basis of the most recent evidence-based clinical practice guidelines¹⁻³. Nonsurgical treatments, including nonsteroidal anti-inflammatory drugs, physical therapy, and intra-articular corticosteroid injections, could provide pain relief, but did not affect structural disease progression. No individual with knee osteoarthritis was deemed eligible for total knee replacement until first failing early treatments; however, we assumed a limited efficacy of these treatments for individuals with advanced knee osteoarthritis.

Incidence of Primary Total Knee Replacement

We estimated the annual incidence of total knee replacement for individuals with end-stage knee osteoarthritis, using two multicenter, longitudinal, observational studies of individuals with knee osteoarthritis: MOST and OAI^{16,17}. We used published data from MOST to derive the overall annual incidence of total knee replacement among individuals with Kellgren-Lawrence grade-3 or 4 knee osteoarthritis²³. We utilized secondary data from the progression subcohort of the OAI to estimate the total knee replacement incidence per person-years at risk (with *at risk* defined as having frequent knee symptoms and Kellgren-Lawrence grade-3 or 4 osteoarthritis), stratified by sex and age (less than sixty-five years versus sixty-five years or older). We used the distribution of age and sex and the relative risk of total knee replacement for each age and sex combination in the OAI data to stratify our MOST-based incidence estimates by age and sex, using published methodology²⁴. Since persons younger than forty-five years and older than eighty-five years of age were not included in the MOST or OAI studies, we conservatively estimated total knee replacement rates in these age groups by reducing annual incidence by 75%, on the basis of national data that show considerably fewer total knee replacements are performed before the age of forty-five years and after the age of eighty-five years⁴. We examined the effect of this assumption by performing a sensitivity analysis, in which we did not reduce the incidence of total knee replacement in these age groups. The resulting incidence rates of total knee replacement among individuals with end-stage knee osteoarthritis (Kellgren-Lawrence grade 3 or 4) are shown in Table I.

To account for variability in both data sources (MOST and OAI), we derived 95% confidence intervals (CI) around each age-specific and sex-specific estimate of the incidence of total knee replacement (Table I)²⁴. We conducted our analysis in a probabilistic fashion, drawing 500 random sets of incidence rates of total knee replacement from the distributions presented in Table I. From this analysis, we calculated the mean and 95% CI around our estimates of the prevalence of total knee replacement. Additionally, because the OAPol Model does not account for secular changes in total knee replacement

TABLE I Model Input Parameters

Parameter	Estimate	Source of Data*
Mean BMI (and stand. dev.) at age of 25 yr† (kg/m^2)		NHANES 2005-2008 ^{20,21}
Male	27.0 $\pm$ 6.1	
Female	27.6 $\pm$ 7.8	
Annual incidence of total knee replacement, given end-stage knee osteoarthritis (95% CI) (%)		Wise et al. ²³ and OAI ¹⁶
<45 yr old		
Male	1.6 (0.8, 2.4)	
Female	2.0 (1.1, 2.9)	
45-64 yr old		
Male	6.4 (3.0, 9.7)	
Female	8.1 (4.5, 11.8)	
65-84 yr old		
Male	11.9 (6.7, 17.0)	
Female	10.9 (6.5, 15.3)	
≥ 85 yr old		
Male	3.0 (1.7, 4.3)	
Female	2.7 (1.6, 3.8)	
Annual failure of total knee replacement leading to revision (%)		Paxton et al. ⁶
<65 yr old		
First year	1.9	
Subsequent years	1.5	
≥ 65 yr old‡		
First year	1.0	
Subsequent years	0.4	

*NHANES = National Health and Nutrition Examination Survey, and OAI = Osteoarthritis Initiative. †BMI = body mass index. ‡For individuals who were eighty-five years of age or older, only 10% of primary total knee replacement failures were revised on the basis of data that show few revision total knee replacements are performed in patients over this age.

utilization over the past few decades, we performed sensitivity analyses, in which we increased and decreased all total knee replacement incidence values by 25% to determine the impact this might have on current prevalence estimates.

Total Knee Replacement Failure and Revision

Rates of total knee replacement failure leading to revision were derived from published data from Kaiser Permanente's large U.S. joint replacement registry⁶. We dichotomized total knee replacement failure rate by first-year compared with subsequent-year failures (Table I). This assumption was based on data suggesting that failure rate and long-term polyethylene wear are linear after the first year^{25,26}. We assumed individuals younger than eighty-five years of age who had a total knee replacement failure accepted revision surgery. We assumed limited (10%) acceptance of revision surgery among individuals who were eighty-five years of age or older, on the basis of data suggesting that few revisions are performed in this age group⁴.

Estimating the Prevalence of Total Knee Replacement

We estimated the prevalence of total knee replacement among adults in the U.S. fifty years of age or older. Using data from the OAPol Model-based simulations, we calculated the proportion of males and females with primary and revision total knee replacement among those alive at each year from the age of fifty to ninety-nine years. We weighted these age and sex-specific prevalence estimates by corresponding U.S. population estimates to determine the prevalence within ten-year age strata (fifty to fifty-nine years, sixty to sixty-nine years, seventy to

seventy-nine years, eighty to eighty-nine years, and ninety years or more)^{27,28}. We combined these age-stratified data to estimate the sex-specific prevalence of primary and revision total knee replacement for individuals fifty years of age and older. For comparison, we similarly estimated the sex-specific prevalence of symptomatic knee osteoarthritis.

Estimating the Number of Adults in the U.S. with Total Knee Replacement

We multiplied estimates of the prevalence of total knee replacement within each ten-year age group by corresponding ten-year population estimates to estimate the number of individuals living with total knee replacement within each age stratum. We separated these results into individuals with primary and revision total knee replacement. We similarly used population estimates in combination with model estimates of the prevalence of knee osteoarthritis to calculate the number of adults in the U.S. who have diagnosed, symptomatic knee osteoarthritis.

Estimating Lifetime Risk of Total Knee Replacement

We used the OAPol Model to calculate the cumulative risk of being diagnosed with knee osteoarthritis and receiving a total knee replacement over the life span, approximated by the time frame between twenty-five and ninety-nine years of age. The cumulative lifetime risk of symptomatic knee osteoarthritis was defined as the proportion of persons who developed symptomatic knee osteoarthritis over their lifetime. Lifetime risk of total knee replacement was defined as the proportion of adults in the U.S. who were diagnosed with

symptomatic knee osteoarthritis over the course of their lifetime and subsequently underwent total knee replacement.

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Results

Prevalence of Total Knee Replacement

We estimated the overall prevalence of total knee replacement among adults in the U.S. fifty years of age or older to be 4.2% (95% CI: 3.7% to 4.6%). The prevalence was higher among females (4.8%) than males (3.4%), and the prevalence increased with each decade of age (Fig. 1). Among males, the prevalence of total knee replacement ranged from 1.3% among those from fifty to fifty-nine years old to >9% among those eighty years of age or older. Among females, the prevalence ranged from 1.9% among those from fifty to fifty-nine years old to >11% among those eighty years of age or older.

Among adults in the U.S. fifty years of age or older, 11.5% had been diagnosed with symptomatic knee osteoarthritis. The percent of adults in the U.S. who had been diagnosed with symptomatic knee osteoarthritis was higher among females (13.3%) than males (9.4%).

Number of Adults in the U.S. Living with Total Knee Replacement

We estimated that 4,007,400 adults (95% CI: 3,583,400 to 4,431,400 adults) in the U.S. over the age of fifty years currently

live with a total knee replacement. Of those, 1,505,900 are male and 2,501,500 are female. Furthermore, we calculated that, of those currently alive with a total knee replacement, 3,471,300 individuals have an intact primary total knee replacement and 536,100 have a revised total knee replacement.

Currently, 265,900 males and 389,900 females from fifty to fifty-nine years old, and another 399,100 males and 585,600 females from sixty to sixty-nine years old, are living with a total knee replacement (Fig. 2). Combining these two age groups, 1,462,200 adults from fifty to sixty-nine years old have an intact primary total knee replacement and 178,300 have a revised total knee replacement. The highest number of individuals with a total knee replacement was found in the seventy to seventy-nine-year-old group (461,000 males and 702,500 females).

Similar OAPol Model projections found that 11,059,800 adults in the U.S. (including those with total knee replacement) are currently diagnosed as having symptomatic knee osteoarthritis. Of the individuals with osteoarthritis, 6,876,700 are female and 4,183,100 are male. We estimated that 31.6% of males and 31.3% of females who are alive and have been diagnosed with symptomatic knee osteoarthritis have an intact primary total knee replacement. An additional 4.4% of males and 5.1% of females who have been diagnosed with knee osteoarthritis have a revision total knee replacement.

Lifetime Risk of Total Knee Replacement

The risk of a twenty-five-year-old adult being diagnosed with symptomatic knee osteoarthritis by the age of sixty years was 8.3% for males and 11.5% for females. The risk of undergoing

Fig. 1

Estimated prevalence of total knee replacement (TKR) in the U.S. by age and sex. Each bar represents the percent of the population with total knee replacement, stratified by age group (increasing from left to right) and sex (blue for male and orange for female). The error bars around each prevalence estimate represent 95% confidence intervals.

Fig. 2

Estimated number of adults in the U.S. living with total knee replacement by age and sex. Each bar represents the number of adults with total knee replacement (TKR), stratified by age group (increasing from left to right) and sex (blue for male and orange for female). The error bars around each estimate represent 95% confidence intervals.

a primary total knee replacement by the age of sixty years was 2.0% (95% CI: 1.3% to 2.6%) for males and 2.8% (95% CI: 2.1% to 3.6%) for females (Fig. 3). The risk of revision total knee replacement by the age of sixty years was <0.4% for both males and females. The lifetime risk of being diagnosed with

knee osteoarthritis was 13.3% for males and 18.8% for females. The lifetime risk of receiving a primary total knee replacement was 7.0% (95% CI: 6.1% to 7.8%) for males and 9.5% (95% CI: 8.5% to 10.5%) for females, and the lifetime risk of undergoing revision total knee replacement surgery was 1.0% (95% CI:

Fig. 3

Estimated risk of primary and revision total knee replacement from the age of twenty-five years by sex. Each bar represents the percent chance that a twenty-five-year-old male or female will undergo total knee replacement (TKR) by the age of sixty years (left two sections) or within his or her lifetime (right two sections). The darker blue bars represent the risk of undergoing a primary total knee replacement, and the lighter blue bars represent the risk of undergoing a revision total knee replacement. The error bars around each estimate represent 95% confidence intervals.

0.8% to 1.3%) for males and 1.7% (95% CI: 1.3% to 2.0%) for females.

On the basis of our estimates, 52.2% of males and 50.6% of females who are diagnosed with symptomatic knee osteoarthritis will receive a primary total knee replacement before death. Among those who undergo a primary total knee replacement, the risk of subsequent revision is 14.9% for males and 17.4% for females.

Sensitivity Analysis

In sensitivity analyses, in which we did not reduce the estimates of the annual incidence of total knee replacement for persons less than forty-five years old and those eighty-five years or older, model estimates of the number of adults living with total knee replacement did not increase by >5%. Increasing and decreasing all age and sex-specific total knee replacement incidence values by 25% led to a range in the prevalence of total knee replacement among adults in the U.S. fifty years of age or older from 3.7% to 4.6%. Estimates of the number of adults in the U.S. living with a total knee replacement ranged from 3,538,700 to 4,446,700. Estimates of the lifetime risk of undergoing primary total knee replacement ranged from 6.3% to 7.5% for males and from 8.7% to 10.2% for females. The lifetime risk of revision total knee replacement ranged from 0.9% to 1.2% for males and from 1.4% to 1.9% for females.

Discussion

We estimated that 4.8% of females and 3.4% of males in the U.S. who are more than fifty years old are currently living with a total knee replacement. This translates to an estimated four million adults in the U.S. with a knee implant, including >500,000 who have undergone revision of the primary total knee replacement. The number of individuals with a total knee replacement represents over one-third of the estimated eleven million adults in the U.S. currently alive who have been diagnosed with symptomatic knee osteoarthritis.

Our model-based estimates suggest that total knee replacement is highly prevalent among older adults in the U.S. Among persons older than fifty years of age, total knee replacement has become considerably more prevalent than rheumatoid arthritis²⁹ and nearly as prevalent as congestive heart failure³⁰. Such comparisons are limited because total knee replacement is not a chronic disease. However, similar to living with a chronic condition, undergoing elective surgery and living with a prosthetic implant lead to increased health-care utilization and carry small but clearly defined health risks, including joint infection, periprosthetic fracture, symptomatic implant loosening, and implant wear¹¹. While annual rates of these adverse outcomes are low, with millions of adults in the U.S. living with total knee replacement over a prolonged period, these complications pose a potentially large public health burden.

Given the frequency of total knee replacement utilization, failed total knee replacements represent a sizeable public health problem. One report has noted that as many as 15% of total knee replacement recipients may experience severe or extreme persistent pain three to four years postoperatively³¹.

These patients often continue to require higher levels of health-care utilization and to experience the disability and reduced quality of life associated with osteoarthritis-related knee pain. Because of their continued disability, individuals with pain after total knee replacement may have low levels of physical activity and be at a heightened risk of death due to other comorbidities compared with the general population³². Moreover, patients with osteoarthritis who have a total knee replacement may experience pain of a type that is more difficult to diagnose and treat than that in patients without a total knee replacement^{11,33}. Given that total knee replacement recipients represent over one-third of adults in the U.S. with diagnosed, symptomatic knee osteoarthritis, refining diagnostic and treatment algorithms should be a priority.

The estimated public health-care burden of total knee replacement is amplified by the fact that nearly 1.5 million adults in the U.S. with an intact primary total knee replacement are between the ages of fifty and sixty-nine years. The existence of this large cohort of young individuals with a total knee replacement is consistent with data suggesting that total knee replacement use has tripled within the forty-five to sixty-four-year-old age group over the past ten years⁵. With recent studies suggesting that younger, healthier patients experience better postoperative outcomes³⁴⁻³⁶, patients wishing to achieve the maximum clinical benefit may be offered and elect total knee replacement at an earlier age. Many of the 1.5 million adults in the U.S. with a total knee replacement will survive for fifteen to twenty years postoperatively, giving them prolonged exposure to complications that may lead to a costly revision arthroplasty. Furthermore, recent data suggest that annual rates of revision for aseptic failure are higher for younger recipients of total knee replacement than for those who are older at the time of surgery^{6,37}. Such findings may indicate that younger individuals, wishing to maintain higher levels of physical activity after surgery, may impose more stress on their knee implants, leading to faster wear rates. The complex role of physical activity, both in improving outcomes after total knee replacement and in increasing the likelihood of complications that may lead to revision, merits further investigation.

The high prevalence of total knee replacement points out the necessity of increasing efforts to prevent osteoarthritis, likely by targeting osteoarthritis risk factors such as obesity and knee injury^{38,39}. Reducing the nationwide prevalence of obesity to levels seen ten years ago could avert >100,000 total knee replacements over the remaining life span for adults in the U.S. who are fifty to eighty-four years old¹⁹.

Our methods of estimating the prevalence and lifetime risk of total knee replacement have several limitations. We estimated the annual incidence of total knee replacement using data from longitudinal osteoarthritis cohorts, which, due to strict selection criteria, may not be representative of the U.S. population with knee osteoarthritis⁴⁰. For example, individuals were excluded from participating in the OAI if they were considering undergoing total knee replacement within the next three years, possibly leading to lower incidence of total knee replacement among the OAI cohort than among the general

U.S. population with end-stage knee osteoarthritis. Consequently, we used data from the MOST study, which did not impose such a restriction, to estimate the magnitude of our incidence estimates and then used data from the OAI study to stratify these estimates by age and sex.

Furthermore, our modeling approach required that we use constant age and sex-specific incidence estimates, although, in reality, the use of total knee replacement among those with end-stage knee osteoarthritis may have changed over time. Data from the OAI and MOST studies were collected in the early 2000s, whereas some individuals currently living with total knee replacement underwent the procedure before the early 2000s, when total knee replacement use was less common^{12,15}. On the other hand, our incidence estimates may be conservative for individuals who underwent total knee replacement in recent years, as the utilization of the procedure has continued to climb since the early 2000s⁵. We accounted for potential variation in total knee replacement incidence over time by performing sensitivity analyses, in which total knee replacement incidence was increased and decreased by 25% across all ages. Even accounting for drastic variation in this pivotal input parameter, estimates of the prevalence of total knee replacement were still approximately 4% to 5% and the number of adults in the U.S. with a total knee replacement remained close to four million. Thus, assuming constant age and sex-specific values of total knee replacement incidence in our modeling approach may not drastically affect the resulting estimates of the current total knee replacement burden in the U.S. Our estimates of the current prevalence and lifetime risk of total knee replacement do not take into consideration future trends in total knee replacement utilization. Some projections have estimated total knee replacement use will continue to grow rapidly in the coming years^{13,41}. On the other hand, our estimates suggest that over one-third of people who have been diagnosed with knee osteoarthritis in the U.S. have already

received a total knee replacement, potentially indicating that, due to high market saturation, the rapid increase in total knee replacement utilization over the last decade⁴ may not be sustained in future years.

Our estimates suggest that total knee replacement is a prevalent condition among adults in the U.S. that may pose a high public health burden. Individuals who have undergone total knee replacement are at risk for several costly and debilitating outcomes, including periprosthetic fracture and joint infection, and are at risk for revision surgery. These outcomes may require specific health services, and knowledge of the number of people who currently live with a total knee replacement is valuable in planning prevention and management strategies. While total knee replacement is a remarkably successful treatment for individuals with end-stage knee osteoarthritis, our findings emphasize the large public health burden posed by the millions of adults in the U.S. living with total knee replacement. ■

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