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CLINICAL RESEARCH

Risk Calculators Predict Failures of Knee and Hip Arthroplasties: Findings from a Large Health Maintenance Organization

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Abstract

Background Considering the cost and risk associated with revision Total knee arthroplasty (TKAs) and Total hip arthroplasty (THAs), steps to prevent these operations will help patients and reduce healthcare costs. Revision risk calculators for patients may reduce revision surgery by supporting clinical decision-making at the point of care.

Questions/purposes We sought to develop a TKA and THA revision risk calculator using data from a large health-maintenance organization's arthroplasty registry and determine the best set of predictors for the revision risk calculator.

Methods Revision risk calculators for THAs and TKAs were developed using a patient cohort from a total joint replacement registry and data from a large US integrated healthcare system. The cohort included all patients who had primary procedures performed in our healthcare system between April 2001 and July 2008 and were followed until January 2014 (TKAs, n = 41,750; THAs, n = 22,721), During the study period, 9% of patients (TKA = 3066/34,686; THA=1898/20,285) were lost to followup and 7% died (TKA= 2350/41,750; THA=1419/20,285). The outcome of interest was revision surgery and was defined as replacement of any component for any reason within 5 years postoperatively. Candidate predictors for the revision risk calculator were limited to preoperative patient demographics, comorbidities, and procedure diagnoses. Logistic regression models were used to identify predictors and the Hosmer-Lemeshow goodness-of-fit test and c-statistic were used to choose final models for the revision risk calculator.

Results The best predictors for the TKA revision risk calculator were age (odds ratio [OR], 0.96; 95% CI, 0.95–0.97; $p < 0.001$), sex (OR, 0.84; 95% CI, 0.75–0.95; $p = 0.004$), square-root BMI (OR, 1.05; 95% CI, 0.99–1.11; $p = 0.140$), diabetes (OR, 1.32; 95% CI, 1.17–1.48; $p < 0.001$), osteoarthritis (OR, 1.16; 95% CI, 0.84–1.62; $p = 0.368$), posttraumatic arthritis (OR, 1.66; 95% CI, 1.07–2.56; $p = 0.022$), and osteonecrosis (OR, 2.54; 95% CI, 1.31–4.92; $p = 0.006$). The best predictors

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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 Kaiser Permanente, San Diego, CA, USA.

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for the THA revision risk calculator were sex (OR, 1.24; 95% CI, 1.05–1.46; p = 0.010), age (OR, 0.98; 95% CI, 0.98–0.99; p < 0.001), square-root BMI (OR, 1.07; 95% CI, 1.00–1.15; p = 0.066), and osteoarthritis (OR, 0.85; 95% CI, 0.66–1.09; p = 0.190).

Conclusions Study model parameters can be used to create web-based calculators. Surgeons can enter personalized patient data in the risk calculators for identification of risk of revision which can be used for clinical decision making at the point of care. Future prospective studies will be needed to validate these calculators and to refine them with time.

Level of Evidence Level III, prognostic study.

Introduction

Total joint arthroplasty is a high-volume and high-cost procedure that can reduce pain and restore function in patients with osteoarthritis [8, 29, 36]. Although most joint arthroplasties can last 15 to 20 years, some fail earlier because of wear and osteolysis, instability, infection, or other causes [1, 10, 32, 34]. These failures often result in revision surgery, which is associated with a greater risk of morbidity and mortality than primary total joint arthroplasty [4, 27]. Not only do revision procedures have a greater risk for complications and mortality, but they also are costly, with complicated revisions sometimes resulting in charges approaching or exceeding USD 100,000 [7, 24].

To minimize the demand of revision total joint arthroplasties, risk factors for failures leading to revisions must be identified. Various factors associated with revision total knee arthroplasty (THAs) and total hip arthroplasty (TKAs) have been reported, including age, sex, diagnosis, BMI, and comorbidities [13, 19, 21, 31, 40]. These known risk factors provide a basis for developing clinical decision aids for patients and surgeons to decide on treatment options after assessing patient-specific risk factors and consequently reduce the risk of revision surgery and enhance quality of care.

Risk calculators are a type of clinical tool that can be used to predict the probability of complications or revisions. Although risk calculators have been created for various diagnoses, procedures, and outcomes, and are used in a range of settings [2, 3, 5, 6, 16, 18, 22, 26, 35, 42–45], risk calculators for total joint arthroplasties have not been developed and fully integrated in large healthcare settings. One risk calculator for periprosthetic joint infection and mortality after THA has been developed however, it was developed only for the Medicare population [5].

The purpose of our study is to describe the development and integration of patient risk calculators, one for revision after THA and one for revision after TKA, for use in a large integrated healthcare system, and to highlight the value of a population-based total joint replacement registry. Although we have used the risk calculators in our large integrated healthcare system (Kaiser Permanente), the results and model parameters were not published. Additional followup for our study population provided an opportunity to update our model parameters and share them for external use and validation. In this study, we sought to develop a TKA and a THA revision risk calculator, using data from a large health-maintenance organization's arthroplasty registry and determine the best set of predictors for the revision risk calculator.

Materials and Methods

We developed revision risk calculators by means of cross-sectional analyses of prospectively collected data from Kaiser Permanente's Total Joint Replacement Registry, comprising data for hip and knee arthroplasties. Kaiser Permanente is an integrated health care system in eight regions of the United States: Northern California, Southern California, Colorado, Northwest, Hawaii, Mid-Atlantic States, Ohio, and Georgia. Registry data collection and validation methods have been described [33, 34]. In brief, the registry uses electronic and paper-based data collection methods to identify patient characteristics, implant, and surgical information. All procedures performed at our institution are captured by the registry . Chart review is conducted to validate the outcomes of interest, including revision. All patients undergoing TKAs (Fig. 1) and TKAs (Fig. 2) registered in the total joint replacement registry between April 2001 and July 2008 were included in the study and followed for a 5-year period (TKAs, n = 41,750; THAs, n =22,721). During the study period, 9% of patients (TKA = 3066/34,686; THA =1898/20,285) were lost to followup owing to membership termination and 7% of patients (TKA = 2350/41,750; THA = 1419/20,285) died. Records with a missing value for any candidate predictor were handled using multiple imputation with Markov chain Monte Carlo method. M = six imputations were created. For the model building step, the M-imputed datasets were stacked into one and a 1/M weight was used to account for the missing data in each covariate. Parameters in the final models were combined with Rubin's rule. Prediction models were developed using a sample that had at least 5 years followup from the available data for the corresponding registry [14]. The sample included 20,592 primary THAs, of which 641 (3.1%) were revised within 5 years postoperatively, and 38,071 primary TKAs, of which 1238 (3.3%) were revised within 5 years postoperatively. Followup for patients with THAs was mean 7.6 years (SD, 1.9) and median 7.4 years (interquartile range [IQR], 6.1–

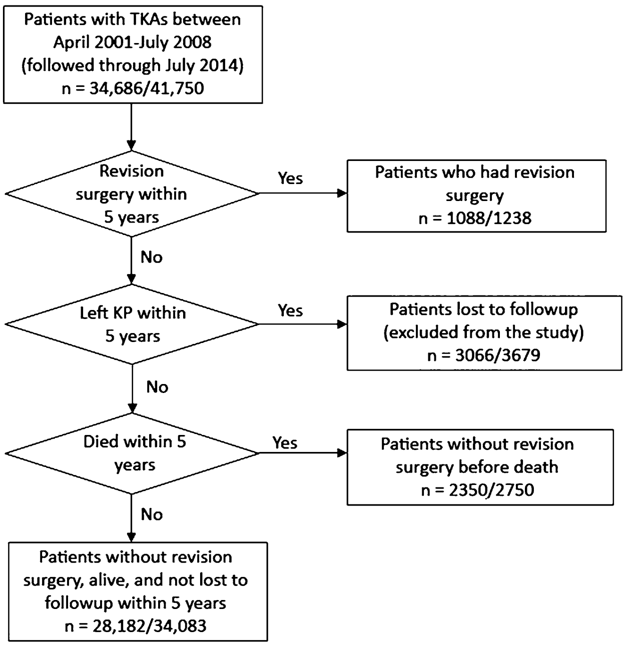

Fig. 1 The flowchart shows the inclusion and exclusion criteria for patients in the study sample who had TKAs. KP = Kaiser Permanente.

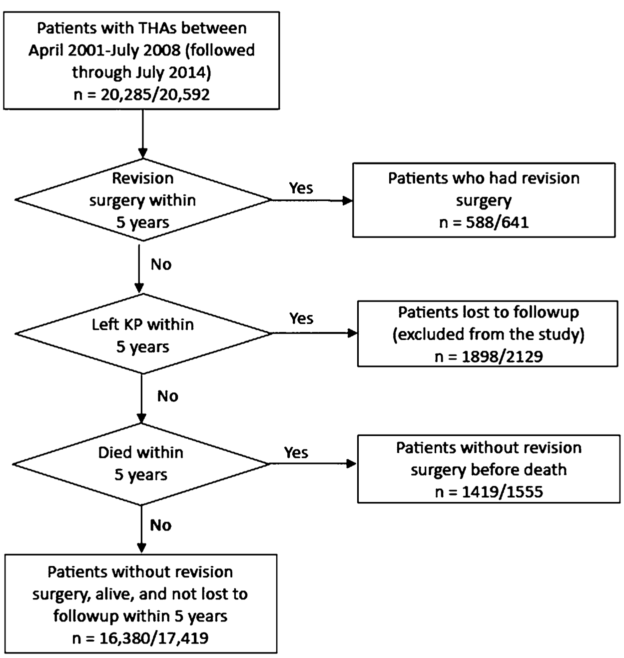

Fig. 2 The flowchart shows the inclusion and exclusion criteria for patients in the study sample who had THAs. KP = Kaiser Permanente.

9.0). Followup for patients with TKAs was mean 7.6 years (SD, 1.9) and median 7.2 years (IQR, 6.0–8.8). The cumulative incidence curves for revision TKA (Fig. 3) and THA are provided (Fig. 4). Institutional review board approval was obtained for this study.

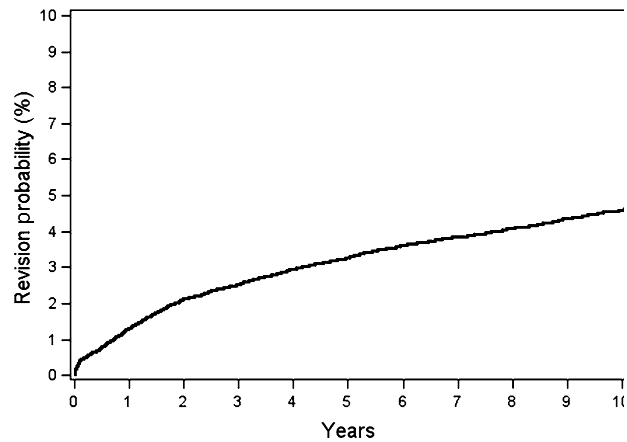

Fig. 3 The cumulative incidence curve of revision for TKA during the followup time is shown.

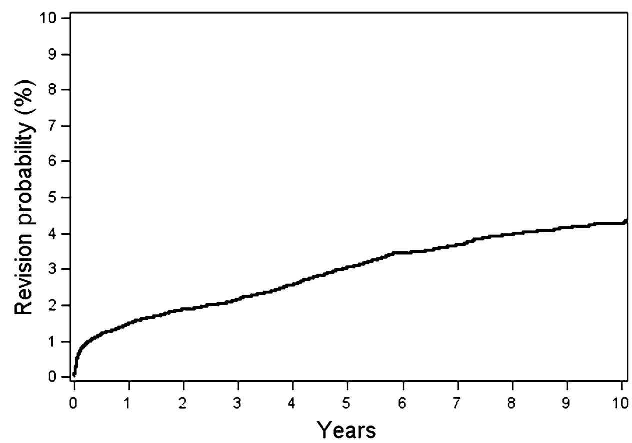

Fig. 4 The cumulative incidence curve of revision for THA during during the followup time is shown.

We solicited input from Kaiser Permanente lead arthroplasty registry surgeons from each of the eight regions (Northern California, Southern California, Hawaii, Northwest, Colorado, Mid-Atlantic, Georgia and Ohio) regarding what variables to consider for use in our revision risk calculators. Variables for possible use were discussed on the basis of aiming to produce a first-generation revision risk calculator that would be as simple and intuitive as possible, consistent with predictive power, that would involve only variables known or knowable at a presurgical office consultation. Candidate predictors included age, sex, BMI, diabetes (yes/no), osteoarthritis (yes/no), inflammatory arthritis (yes/no), posttraumatic arthritis (yes/no), rheumatoid arthritis (yes/no), and osteonecrosis (yes/no). On this basis, the American Society of Anesthesiologists score, for example, although having apparent predictive power but not available before the time of the procedure, could not be considered for these prediction models.

For hips and knees individually, various subsets of candidate predictors were examined. Those with higher predictive power were input to a program, the mfp (multivariable fractional polynomial) macro [30, 39], to see what functional form of each continuous predictor (BMI, age) might be best for our prediction models. The mfp macro can test a wide variety of prespecified functional forms for each continuous predictor, such as linear, second and third powers, square and cube roots, inverse and log transforms, and two-term sums of such transformations, and it can select an optimal model based on default or specified selection criteria. Although use of restricted cubic splines would be an alternative approach to capturing functional form, the mfp approach provided the prospect of combining flexible functional form modeling with being able to understand the functional form involved in terms of a relatively simple, small number of standard polynomial, and other familiar mathematical forms [38]. Some interaction terms were examined.

Given its status, unlike some other candidate risk factors as potentially modifiable before surgery, we aimed to assess the role of BMI in predicting revision as carefully as possible to facilitate insight in how weight reduction might possibly decrease the risk of revision surgery. We used the mfp macro to examine a large variety of possible functional forms for BMI in particular; for our knee risk predictor, for example, we checked functions of BMI through the fifth power and the fourth power with various functional forms for age and various transforms of BMI on cases with restricted ranges of BMI values.

Both of our calculators model the risk of a first subsequent revision of any cause within 5 years postoperatively and do not consider any possible subsequent revisions of the same procedure. Risk of revision was modeled by logistic regression. Although a wide variety of methods for developing prediction models is available, our approach was guided with the intent to combine predictive ability with understanding and assessing the clinical plausibility and relevance of the contribution of each predictor used in our models, which could facilitate acceptance and use among surgeons and patients. We therefore avoided predictive models that do not provide insights regarding the parameter being approximated. Candidate predictors were selected from preoperative patient characteristics on the basis of clinical knowledge with an additional criterion of being readily available from an integrated healthcare system's routinely collected data (for example, outpatient and inpatient electronic health record, administrative data, and Geographically Enriched Member Sociodemographics data) or easily determinable at the time of consultation.

We used the c-statistic in combination with the Hosmer-Lemeshow goodness-of-fit criterion to do initial sorting of candidate models. Second-round selection of models was based on assessment by the c-statistic criterion alone. Cross-validation for model checking and final selection from among the five prediction models with the best c-statistic was done using 90% to 95% subsamples, specifically, 10 samples each consisting of 95% of the original data (simple random sampling) were used to evaluate the models [14]. In addition, the observed and predicted numbers of revisions by revision risk probability deciles were compared.

Sensitivity Analysis

Adjustment for patient clustering (some patients had both knees or both hips replaced) had no effect on results and therefore was not included in final models. Interaction terms were tested but not retained because they did not improve any of the models.

All analyses were performed in SAS® 9.1.3 (SAS Institute Inc, Cary, NC, USA).

Results

Knee Revision Risk Calculator

Predictors selected for the final model included age, BMI, gender, diabetes (yes/no), osteoarthritis (yes/no), posttraumatic arthritis (yes/no), and osteonecrosis (yes/no). The square-root of BMI was used, whereas age was incorporated as a linear term (Table 1). Our knee model predicted well in the lowest and midrange decile of risk, lowest: 56 revisions predicted versus an observed 60, and 6th decile: 119 revision predicted versus and 117 observed, and did least well in the highest decile (Table 2). Patients in the highest decile of risk were four times more likely to have a revision TKA than those in the lowest decile of risk, with the most risky 10% of patients experiencing 22% of all revisions and the least risky 10% undergoing 5% of all revisions (Fig. 5).

Table 1. Variables in the primary total knee replacement revision risk calculator

Variable	Odds ratio (95% CI)	p value
Age	0.96 (0.95–0.97)	< 0.001
Sex	0.84 (0.75–0.95)	0.004
Diabetes	1.32 (1.17–1.48)	< 0.001
Osteoarthritis	1.16 (0.84–1.62)	0.368
Posttraumatic arthritis	1.66 (1.07–2.56)	0.022
Osteonecrosis	2.54 (1.31–4.92)	0.006
Square-root BMI	1.05 (0.99–1.11)	0.140

Table 2. Observed and predicted revisions by deciles

Decile	Hip		Knee	
	Observed number	Predicted number	Observed number	Predicted number
Lowest	56	43	61	56
2nd	47	49	68	71
3rd	47	53	83	83
4th	51	56	105	94
5th	54	59	95	106
6th	57	63	117	119
7th	54	67	140	133
8th	76	72	126	151
9th	95	79	164	177
Highest	104	99	279	248

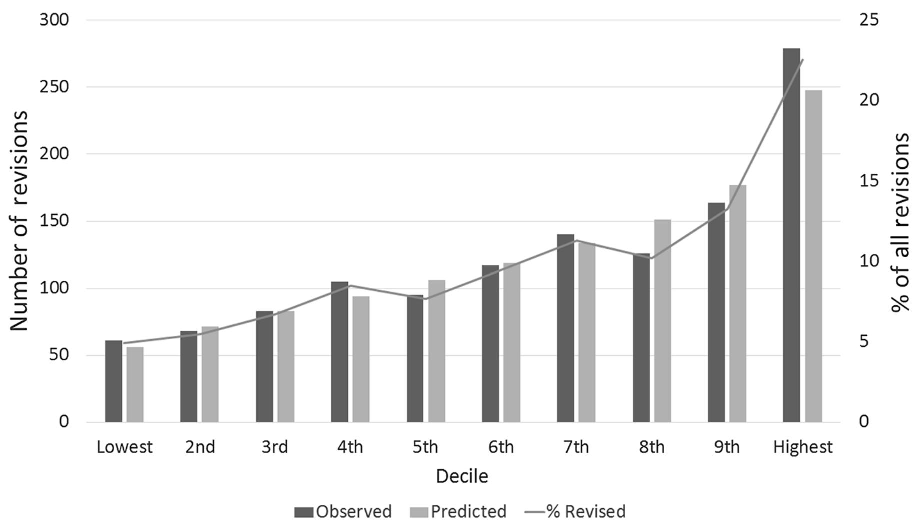

Fig. 5 Observed and model-predicted numbers of revision within 5 years of total knee replacement by revision risk decile and percent of revisions attributed to each risk decile are shown.

Hip Revision Risk Calculator

Predictors selected for the final model were gender, BMI, age, and osteoarthritis. Similar to the final knee risk prediction model, the square-root of BMI and linear term of age were used (Table 3).The hip model predicted less well in the highest decile than the knee model, 99 predicted cases versus an observed 104, but better in the midrange and lowest decile, where it predicted 43 cases versus an observed 56 (Table 2). Patients in the highest decile of risk were 1.9 times more likely to have a revision THA than those in the lowest decile of risk, with the most risky 10% of patients experiencing 16% of all revisions and the least risky 10% undergoing 9% of all revisions (Fig. 6).

Application Development

Model parameters were entered in Excel (Microsoft® Inc, Redmond, WA, USA) spreadsheet algorithms to allow creation of limited-use websites at which Kaiser Permanente orthopaedic surgeons can now enter patient data to obtain a predicted revision probability. This is given as an absolute risk rather than as any kind of relative risk or odds ratio. For instance, an 81-year-old female, 5 feet, 5 inches tall, 130 pounds (BMI = 21.6 kg/m^2) with ostheoarthritis and diabetes, is expected to have a 1.9% risk of revision within 5 years after a TKA. A 50-year-old male, 6 feet tall, 225 pounds (BMI = 30.5 kg/m^2), with diabetes, is expected to have a 4.0% risk of revision within 5 years after a THA. The model parameters for the revision risk calculators are provided for external use and validation (Fig. 7).

Other Relevant Findings

Odds ratios for the predictors in the revision risk calculators are shown (Tables 1 and 3). The odds ratios for BMI in each model are not simple to interpret because they represent the increase in odds of revision for a one-unit increase in the square root of BMI. Thus, an increase of BMI from 25 to 26 would involve a $\sqrt{26} - \sqrt{25} = 5.09902 - 5 = 0.09902$ unit increase in square root BMI. Because $(1.067322)^{0.09902} = 1.006472$, this increase in BMI represents an approximately 1% increase in the odds of having a revision TKA. For further comparison, a BMI of 40 kg/m^2 represents an increase in odds of a knee revision of approximately 6% compared with a BMI of 30 kg/m^2.

Table 3. Variables in the primary total hip replacement revision risk calculator

Variable	Odds ratio	p value
Age	0.98 (0.98–0.99)	< 0.001
Sex	1.24 (1.05–1.46)	0.010
Osteoarthritis	0.85 (0.66–1.09)	0.190
Square-root BMI	1.07 (1.00–1.15)	0.066

Discussion

The risks and demands associated with revision TKA and THA are a significant healthcare concern for patients, clinicians, healthcare systems, and payers. Methods to prevent or reduce revision rates can improve care and reduce healthcare costs. This study identified a set of predictor variables for TKA and THA revision risk calculators from a large integrated healthcare system. The model parameters from this study can be used for other patients' revision risk calculation and validation.

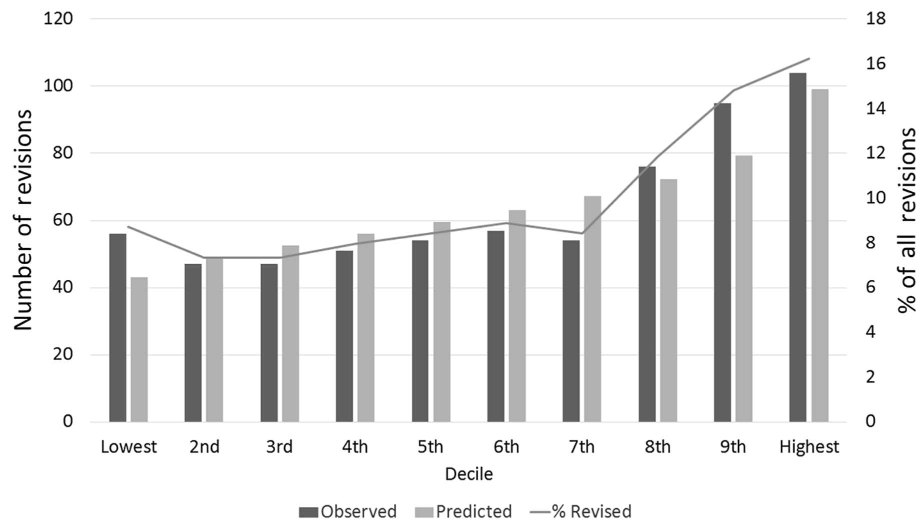

Fig. 6 Observed and model-predicted numbers of revision within 5 years of total hip replacement by revision risk decile and percent of revisions attributed to each risk decile are presented.

Fig. 7 The model parameters used to create the revision risk calculators for use in additional settings and external validation, are shown.

Knee Formula:

```
efAge = cAge * -0.04121
efBMI = 0.044426 * sqrt(cBMI)
efGender = Female* -0.17099
efDiab = dm * 0.27649
efOsteoarthritis = Osteoarthritis * 0.152503
efPTA = PTA * 0.505203
efOsteonecrosis = Osteonecrosis * 0.930812

Bx = -1.08118 + efAge + efGender + efBMI + efDiab + efOsteoarthritis + efPTA + efOsteonecrosis
```

Knee_Risk_pct = (Math.exp(Bx) * 100 / (1 + Math.exp(Bx)))

~~~~~~

Hip Formula:

```
efAge = cAge * -0.01742
efBMI = 0.067322 * sqrt(cBMI)
efGender = female* 0.215285
efOsteoarthritis = Osteoarthritis * -0.16622

Bx = -2.66834 + efAge + efGender + efBMI + efOsteoarthritis
```

Hip_Risk_pct = (Math.exp(Bx) * 100 / (1 + Math.exp(Bx)))
~~~~~~

Since the revision risk calculators were based on available data from our integrated healthcare system, generalizability beyond our healthcare system has not been established and is a limitation of the study. However, our patient membership has been shown to reflect the sociodemographic makeup of the entire corresponding census region population for large regional subsets [23]. More extensive validation outside the integrated healthcare system is still necessary to ensure generalizability of these revision risk calculators. The model parameters are specifically included in this study for use and validation of the models beyond our organization and for development and refinement of revision risk calculators in other settings. Another potential limitation of this study is the focus on all-cause revision. Predictors of revisions may differ associated with the mechanism of failure and should be examined in future studies. However, all-cause revision is a standard endpoint for many registry-related studies. Missing BMI values (3%) also were a study limitation but they were addressed using multiple imputation. Finally, the study focused on 5-year revision rates and does not evaluate longer-term (eg, 10-20 years) risk of revision.

Similar to other studies that have examined revision risk factors, we identified sex, age, BMI, diagnosis, and diabetes as patient risk factors of revision [17, 28, 40, 41]. Two studies [5, 37] examined predictors for inclusion in total joint arthroplasty risk calculators. One study [5] investigated periprosthetic joint infection and mortality but was limited to Medicare administrative data and did not evaluate longer-term risk of revision [5]. Another study [37] examined perioperative risk predictors for use in a risk calculator but was limited to one institution and did not evaluate risk of revision. THA and TKA revision rates in our study were similar to published rates [9, 11, 12, 15]. Revision per 100 observation-years was slightly lower than those reported by other national registries [25]. In addition, revision burden was lower than that reported by Medicare [20, 24]. The similarities in findings suggest that our revision risk calculators may generalize to other settings.

The THA and TKA risk calculators are used in our system for clinical decision making at the point of care. Clinical applications of these calculators include weight counseling to show the reduction in risk associated with ideal versus current weight, management of preoperative anxiety by providing patients with their personalized risk so they understand the procedure and their potential results, addressing diabetic concerns regarding complication risks so they know complication risk may be slightly higher but that they are candidates for good outcomes, and setting patient expectations, such as for younger patients in particular who want to know how long the prosthesis will last.

The next versions of these revision risk calculators should benefit from surgeon feedback concerning additional candidate predictors to examine, such as prior knee surgery for the knee revision risk calculator, steroid use, hemoglobin A1c levels, and ways to improve calculator web site interface design. They also will have more risk data from more cases, with several years more followup, and with reduced numbers of missing data in predictors such as BMI. They also may benefit from the availability of substantially expanded amounts of information in registry data on comorbidities (and racial/ethnic classification), which creates the possibility of including some of these variables as predictors. In addition, implant and surgical technique variables may further expand the predictive use of these tools to consider a range of possible options for surgery for a given patient. Finally, the incorporation of implant, procedure, surgeon, and/or site-specific information that becomes available at or after the time of surgery may facilitate the development of postoperative risk calculators that lead to more refined surveillance and monitoring after a joint arthroplasty.

TKA and THA revision risk calculators were predictive of revision and were integrated in our healthcare setting using a web-based system. The model parameters are presented for use by other patients and clinicians in various settings and for external validation. Identification of risk factors to influence treatment decisions may reduce revision total joint arthroplasties and enhance quality of care.

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