Research Article

Robotic Arm-assisted Total Hip Arthroplasty is More Cost-Effective Than Manual Total Hip Arthroplasty: A Markov Model Analysis

David R. Maldonado, MD
Cammille C. Go, BS
Cynthia Kyin, BA
Philip J. Rosinsky, MD
Jacob Shapira, MD
Ajay C. Lall, MD, MS
Benjamin G. Domb, MD

Abstract

Background: Total hip arthroplasty (THA) is the benchmark surgical treatment of advanced and symptomatic hip osteoarthritis. Preliminary evidence suggests that the robotic arm-assisted (RAA) technology yields more accurate and reproducible acetabular cup placement, which may improve survival rate and clinical results, but economic considerations are less well-defined. The purpose of this study was to compare the cost effectiveness of the RAA THA with manual THA (mTHA) modalities, considering direct medical costs and utilities from a payer's perspective.

Methods: A Markov model was constructed to analyze two potential interventions for hip osteoarthritis and degenerative joint disorder: RAA THA and mTHA. Potential outcomes of THA were categorized into the transition states: infection, dislocation, no major complications, or revision. Cumulative costs and utilities were assessed using a cycle length of 1 year over a time horizon of 5 years.

Results: RAA THA cohort was cost effective relative to mTHA cohort for cumulative Medicare and cumulative private payer insurance costs over the 5-year period. RAA THA cost saving had an average differential of $945 for Medicare and $1,810 for private insurance relative to mTHA while generating slightly more utility (0.04 quality-adjusted life year). The preferred treatment was sensitive to the utilities generated by successful RAA THA and mTHA. Microsimulations indicated that RAA THA was cost effective in 99.4% of cases.

Conclusions: In the Medicare and private payer scenarios, RAA THA is more cost effective than conventional mTHA when considering direct medical costs from a payer's perspective.

Level of Evidence: Economic Level III. Computer simulation model (Markov model)

From American Hip Institute (Dr. Lall and Dr. Domb), American Hip Institute Research Foundation (Dr. Maldonado, Ms. Kyin, Dr. Rosinsky, Dr. Shapira, Dr. Lall, and Dr. Domb), Des Plaines, IL, AMITA Health St. Alexius Medical Center, Hoffman Estates, IL (Dr. Lall and Dr. Domb), and Perelman School of Medicine at the University of Pennsylvania, Philadelphia, PA (Ms. Go).

Correspondence to Dr. Domb: DrDomb@americanhipinstitute.org

This study was performed in accordance with the ethical standards in the 1964 Declaration of Helsinki. This study was carried out in accordance with relevant regulations of the US Health Insurance Portability and Accountability Act (HIPAA). Details that might disclose the identity of the subjects under study have been omitted. This study was approved by the IRB (IRB ID: 5276).

J Am Acad Orthop Surg 2020;00:1-9

DOI: 10.5435/JAAOS-D-20-00498

Osteoarthritis (OA), one of the most common forms of joint disease, is a major cause of hip pain and functional disability. Resulting pain and stiffness can decrease the quality of life and impair patient ability to perform activities of daily living. As the 11th highest contributor to global disability, the incidence of hip OA worldwide is 0.85%, affecting 10% of men and 18% of women aged older than 60 years.[1] This incidence is only expected to increase, in part because of an aging society.[2] Furthermore, the costs associated with OA can be considerable, with total annual direct costs for patients with OA were estimated to be over two times higher than similar patients without the condition.[3,4] The annual average direct cost—hospitalization, emergency department visits, physician visits, outpatient visits, medications, and others—has been estimated to vary from $1,442 to $21,335 in the United States, placing a strain on the limited health care resources available.[5] Substantial indirect costs—absenteeism, presenteeism, disability, and worker's compensation, which range from an average of $238 to $29,935—serve to further increase the economic burden of OA.[5]

Total hip arthroplasty (THA) is considered the treatment of choice for end-stage OA, resulting in favorable functional outcomes and substantially increased quality of life.[6,7] In most cases, patients can expect their hip arthroplasty to last at least 25 years.[8] Owing to the increasing incidence of OA, the demand for primary THA has been projected to likewise increase by severalfold by 2030.[9] Furthermore, dislocation after primary THA continues to be a prevalent and costly complication that diminishes the cost effectiveness of an otherwise very successful surgical procedure. The average hospital costs of one or more closed reductions and the subsequent revisions represented 148% of the hospital cost of an uncomplicated primary total hip arthroplasty.[10] Placing the acetabular implant in a target zone may not eliminate the risk of dislocation, but it could possibly minimize this risk, as such, meticulous attention to component position is key.[11]

Robotic arm-assisted (RAA) THA offers several advantages over conventional or manual THA (mTHA). RAA THA surgery allows the surgeon to translate preoperative planning to intraoperative execution with surgical accuracy and precision.[12,13] The ability to execute a precise preoperative plan during surgery through RAA THA may benefit less experienced surgeons.[14] RAA THA has also been reported to have markedly higher accuracy when positioning implants in THA,[13,15-17] which is key for long-term implant survivorship. Illgen et al,[17] reported 0% dislocation rate after primary RAA THA at the 2-year follow-up in a cohort of 100 consecutives patients. Given that the costs associated with THA can be substantial, there exists a need for an economic evaluation to determine the relative merits of new technology in THA surgery.

The purpose of this study was to compare the cost effectiveness of the

Dr. Maldonado or an immediate family member has received non-financial support from Arthrex; has received non-financial support from Stryker; has received non-financial support from Smith & Nephew; has received non-financial support from Ossur, outside the submitted work; and Dr. Maldonado is an editorial board member of the *Journal of Arthroscopy*. Dr. Rosinsky or an immediate family member has received non-financial support from Arthrex; has received non-financial support from Stryker; has received non-financial support from Smith & Nephew; and has received non-financial support from Ossur, outside the submitted work. Dr. Shapira or an immediate family member has received non-financial support from Arthrex; has received non-financial support from Stryker; has received non-financial support from Smith & Nephew; and has received non-financial support from Ossur, outside the submitted work. Dr. Lall or an immediate family member has received grants, personal fees and non-financial support from Arthrex; has received non-financial support from Iroko; has received non-financial support from Medwest; has received non-financial support from Smith & Nephew; has received grants and non-financial support from Stryker; has received non-financial support from Vericel; has received non-financial support from Zimmer Biomet; has received personal fees from Graymont Medical, outside the submitted work; and Dr. Lall is the Medical Director of Hip Preservation at St. Alexius Medical Center. Dr. Domb or an immediate family member has received grants and other from American Orthopedic Foundation, during the conduct of the study; has received personal fees from Adventist Hinsdale Hospital; has received personal fees and non-financial support from Amplitude; has received grants, personal fees and non-financial support from Arthrex; has received personal fees and non-financial support from DJO Global; has received grants from Kaufman Foundation; has received grants, personal fees and non-financial support from Medacta; has received grants, personal fees, non-financial support and other from Pacira Pharmaceuticals; has received grants, personal fees, non-financial support and other from Stryker; has received grants from Breg; has received personal fees from Orthomerica; has received grants, personal fees, non-financial support and other from Mako Surgical Corp; has received grants and non-financial support from Medwest Associates; has received grants from ATI Physical Therapy; has received grants, personal fees and non-financial support from St. Alexius Medical Center; has received grants from Ossur, outside the submitted work; In addition, Dr. Domb has a patent 8920497—Method and instrumentation for acetabular labrum reconstruction with royalties paid to Arthrex, a patent 8708941—Adjustable multi-component hip orthosis with royalties paid to Orthomerica and DJO Global, and a patent 9737292—Knotless suture anchors and methods of tissue repair with royalties paid to Arthrex and Dr. Domb is the Medical Director of Hip Preservation at St. Alexius Medical Center, a board member for the American Hip Institute Research Foundation, AANA Learning Center Committee, the *Journal of Hip Preservation Surgery*, the *Journal of Arthroscopy*; and has HAD ownership interests in the American Hip Institute, Hinsdale Orthopedic Associates, Hinsdale Orthopedic Imaging, SCD#3, North Shore Surgical Suites, and Munster Specialty Surgery Center. Neither of the following authors nor any immediate family member has received anything of value from or has stock or stock options held in a commercial company or institution related directly or indirectly to the subject of this article: Ms. Go and Ms. Kyin.

Supplemental digital content is available for this article. Direct URL citation appears in the printed text and is provided in the HTML and PDF versions of this article on the journal's Web site (www.jaaos.org).

RAA THA with mTHA modalities, considering direct medical costs and utilities from a payer's perspective. Our primary hypothesis was that RAA THA would be cost effective for payers over medium-term follow-up. This analysis strictly considers direct medical costs and utilities to the payer as a consequence of surgical treatment choice to inform payers about viability of the relative THA modalities.

Methods

Model Structure

Using TreeAge Pro 2019 (TreeAge Software), a Markov model was constructed to analyze two potential interventions for hip OA and degenerative joint disorder: RAA THA and mTHA[18] (Figure 1). Markov models are stochastic models used to model randomly changing systems in which it is assumed that no time dependence exists on its probability distribution, and the future state depends only on the current state. There is no memory, which means future states are independent from events occurring previously. Importantly, transition probabilities from one state to another are not explicitly dependent on time.[18] Subsequently, the model represents all possible disease states and the consequences of intervention in a mutually exclusive and exhaustive manner. The transition between states corresponds to condition changes over time, as defined by transition probabilities. The potential outcomes of THA were categorized into the transition states of infection, dislocation, or no major complications. All patients could also potentially transition to revision THA, and, in certain cases, re-revision THA. Cumulative costs were assessed using a cycle length of 1 year over a time horizon of 5 years.

For purposes of this model, several assumptions were required: (1) correct diagnosis, (2) appropriate treatment, (3) identical rates of revision after infection and dislocation for RAA THA and mTHA, (4) identical rates of re-revision for RAA THA and mTHA, and (5) the terminal state for patients was re-revision (ie, re-re-revision was not possible).

Transition Probabilities

Data for the mTHA and revision THA were extracted from sources available from the literature (35 to 40). Transition probabilities for RAA THA were derived from prospectively collected data on a cohort of patients who had a primary THA from June 2011 to October 2017 at our institution (American Hip Institute). All procedures were performed by the senior author (B.G.D.) using the MAKO RAA (MAKO Surgical [Stryker]). Patients were eligible for this study if they had a minimum 1-year follow-up and were older than 21 years of age. Exclusion criteria were patients with a body mass index ≥40 kg/m^2 or had a systemic infection. All data collection received Institutional Review Board Approval.

Transition probabilities for the base case were calculated by dividing the number of events over the patient-year of the follow-up. For example, if 10 patients dislocated of the 100 patients had follow-up, the transition probability would be 0.10.[19]

During the study period, there were 555 patients who underwent RAA THA and met all the inclusion and exclusion criteria. The mean age was 59.2 ± 9.7 years, with a follow-up of 34.3 ± 17.7 months. Further patient characteristics are included in Table 1. Over the 5-year follow-up, seven patients (1.3%) developed an infection, one patient (0.2%) had a dislocation, and five patients (0.9%) required a revision THA.

Utilities

Utilities were expressed in quality-adjusted life year (QALY), ranging from 0 (death) to 1 (perfect health). Where possible, utilities were derived from the literature with the exception of RAA THA, which was calculated from clinical data. Utility for this state was calculated using a method described by Chang et al[20] and Shearer et al,[21] which provided a conversion between Harris Hip Score and QALY. A discount rate of 3% was applied to reflect the present value of utilities.[22]

Payer Costs

All costs for the Markov model were obtained from the Inpatient Medicare 100% Standard Analytic File[23] compiled by the Centers for Medicare and Medicaid Services and is representative of nearly 37 million Medicare Fee-for-Service beneficiaries. The analysis included patients who received either a RAA THA or mTHA from July 1, 2018, to June 30, 2019. The International Classification of Diseases, 10th Revision, and Current Procedural Terminology codes were used to identify inpatient procedures (Table, Supplemental Digital Content 1, http://links.lww.com/JAAOS/A518). Costs for this analysis are defined as payments made by Medicare for each of the services rendered (including infection and dislocation with no revision, revision, or re-revision). Private payer costs were derived by applying a multiplier (1.68) taken from previous orthopaedic cost effectiveness literature to the Medicare payments.[19] Only direct costs from a payer's perspective were considered.

Statistical Analysis

TreeAge Pro 2019 was used to construct and analyze the Markov model. For data taken from the patient registry, an estimate of 0.001 (0.1%) was used when no events for a specific transition state were reported for a particular year.[19] Costs were reported in 2019 USA dollars ($) with a

Figure 1

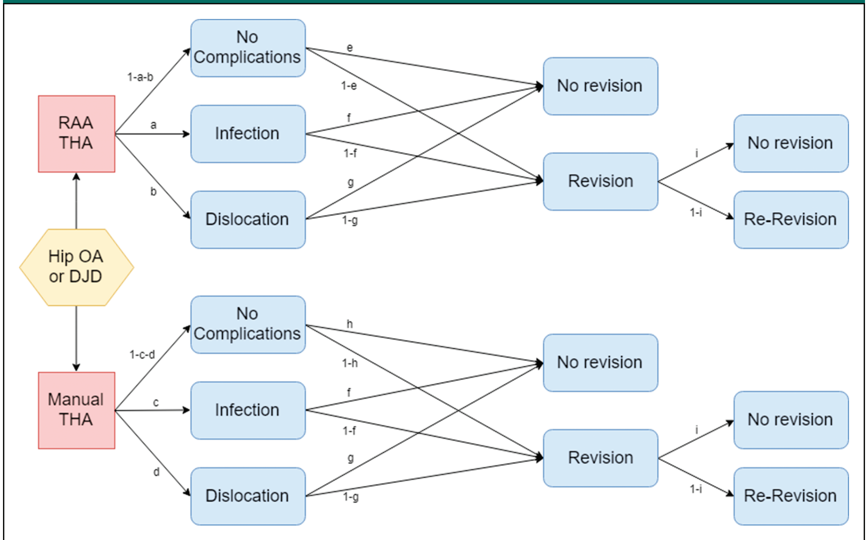


Chart showing the Markov model. Health state diagram. The yellow hexagon represents the diagnosis, red squares represent the interventions, and blue rectangles are the potential transition states. Letters represent the potential transition probabilities. DJD = degenerative joint disease, OA = osteoarthritis, RAA = robotic arm-assisted, THA = total hip arthroplasty

Table 1

Patient Demographics of RAA THA

Variable	RAA THA
n	555
Age (yr)	59.2 ± 9.7 (28.4-90.5)
Sex	
Male	257 (46.3%)
Female	298 (53.7%)
Body mass index	28.9 ± 4.7 (15.4-39.9)
Follow-up time (mo)	34.3 ± 17.7 (12-85.2)

RAA = robotic arm-assisted, THA = total hip arthroplasty
Values are reported in the form of mean ± SD (range).

discounting rate of 3% per year.[22] For the 1-way sensitivity analyses, model parameters were individually varied by 10%.[24] A parameter was considered sensitive if it changed the preferred treatment strategy. For the probabilistic sensitivity analysis, a gamma type distribution was applied to all costs.[21,25] All Markov model inputs are reported in Table 2.

The primary outcome for determining cost effectiveness was the incremental cost-effectiveness ratio (ICER), which is the difference in costs between the treatment and the comparator divided by the difference in utilities (ie, ICER = Δ Costs/Δ Effectiveness). A treatment strategy was determined to be cost effective if the ICER was less than the selected willingness-to-pay (WTP) threshold of $50,000 per QALY.[26,27] WTP thresholds have been suggested, ranging from $50,000 to $150,000 per QALY,[28] but the $50,000 per QALY threshold was selected to ensure a more conservative analysis. In the cases where a treatment strategy both costs less and provides more utility, it can be termed "dominant."

Results

Reference Case

For the reference case, RAA THA was both less costly and more effective than mTHA. At the 5-year time point, mean cumulative Medicare costs were $14,410 ± 40 and $15,355 ± 115 for RAA THA and mTHA, respectively, whereas the mean cumulative private payer costs were $15,212 ± 82 and $17,022 ± 204, respectively. The mean cumulative utilities were 2.96 ± 0.58 and 2.92 ± 0.57 QALY for RAA THA and mTHA, respectively. Thus, RAA THA cost saving had an average differential of $945 for Medicare and $1,810 for private insurance relative to mTHA. The calculated ICER for Medicare was −$23,625 per QALY. The ICER was negative because RAA THA was dominant over mTHA, being both less costly and more effective.

Sensitivity Analyses

Model parameters were varied individually by 10% as part of the 1-way sensitivity analyses to determine which parameters had the greatest impact on cost effectiveness.[24] A tornado diagram was created to show the impact of each parameter on ICER (Figure 2). Only two parameters were sensitive and affected preferred treatment strategy: utility of RAA THA and utility of mTHA. Although not sensitive, costs of infection and dislocation had the next-most impact on the treatment of choice.

One hundred thousand microsimulations were run to assess the potential variability of outcomes among patients. At the selected WTP threshold

Table 2

Markov Model Inputs Used

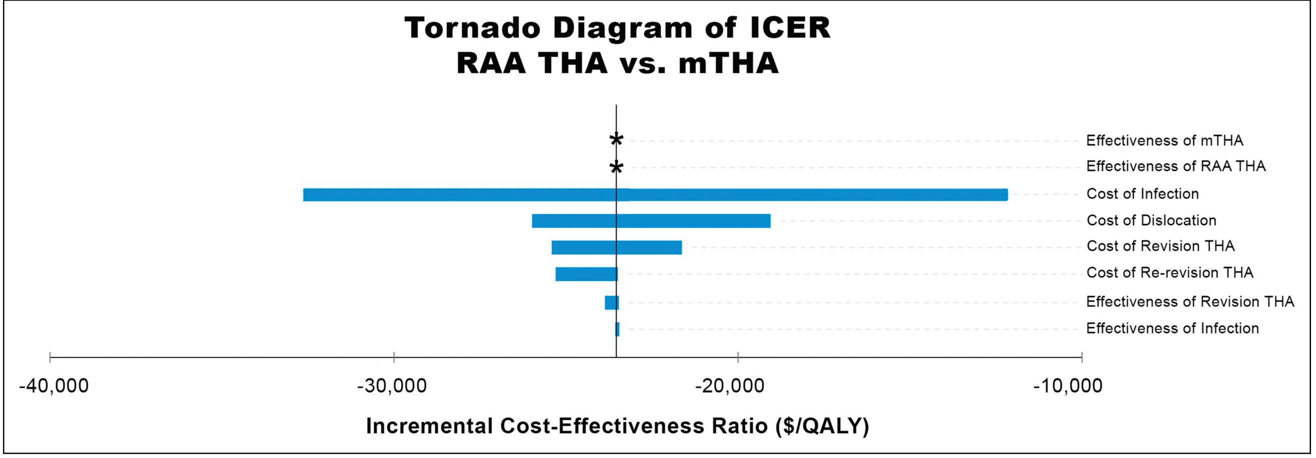
Transition State	Transition Probability	Base	Source
Infection after RAA THA	a	0.013	Clinical data
Dislocation after RAA THA 1 yr	b1	0.002	Clinical data
Dislocation after RAA THA 2 yr	b2	0.001	Clinical data
Dislocation after RAA THA 3 yr	b3	0.001	Clinical data
Dislocation after RAA THA 4 yr	b4	0.001	Clinical data
Dislocation after RAA THA 5 yr	b5	0.001	Clinical data
Infection after mTHA	c	0.017	37, 38
Dislocation after mTHA 1 yr	d1	0.006	39
Dislocation after mTHA 2 yr	d2	0.001	39
Dislocation after mTHA 3 yr	d3	0.001	39
Dislocation after mTHA 4 yr	d4	0.001	39
Dislocation after mTHA 5 yr	d5	0.001	39
Revision after no complication RAA THA 1 yr	e1	0.005	Clinical data
Revision after no complication RAA THA 2 yr	e2	0.005	Clinical data
Revision after no complication RAA THA 3 yr	e3	0.001	Clinical data
Revision after no complication RAA THA 4 yr	e4	0.001	Clinical data
Revision after no complication RAA THA 5 yr	e5	0.001	Clinical data
Revision after infection	f	0.044	40
Revision after dislocation	g	0.061	41
Revision after no complication mTHA 1 yr	h1	0.024	42
Revision after no complication mTHA 2 yr	h2	0.020	42
Revision after no complication mTHA 3 yr	h3	0.015	42
Revision after no complication mTHA 4 yr	h4	0.014	42
Revision after no complication mTHA 5 yr	h5	0.012	42
Re-revision THA	i	0.018	38

Utility (QALY)	Base	Source
Utility of mTHA	0.88	43
Utility of RAA THA	0.89	Clinical data
Infection after THA	0.72	6
Dislocation after THA	0.51	44
Revision THA	0.75	6,45
Re-revision THA	0.72	46

Costs	Base
mTHA	$13,408.40
RAA THA	$13,590.76
Infection	$22,512.69
Dislocation	$18,437.47
Revision	$17,388.39

$ = US dollars, mTHA = manual THA, QALY = quality-adjusted life year, RAA = robotic arm-assisted, THA = total hip arthroplasty

Figure 2



Tornado diagram of the Medicare cost differential ranges for mTHA versus RAA THA. Tornado diagram of the Medicare cost differential ranges for mTHA versus RAA THA, resulting from 1-way sensitivity analyses in which the different costs were individually varied by 10%. Only the top eight most impactful parameters are shown. The black line represents the ICER of −$23,625 per QALY for the reference case. ICER = incremental cost-effectiveness ratio, mTHA = manual total hip arthroplasty, QALY = quality-adjusted life year, RAA = robotic arm-assisted, THA = total hip arthroplasty

of $50,000/QALY, RAA THA was determined to be more cost effective than mTHA in 99.4% of the cases (Figure 3). Probabilistic sensitivity analysis indicated that cumulative Medicare costs at 5 years ranged from $14,274 to $14,456 for RAA THA and from $14,646 to $15,084 for mTHA (Figure 4). Cumulative private payer costs ranged from $15,012 to $15.411 for RAA THA and $16,526 to $17,516 for mTHA.

Discussion

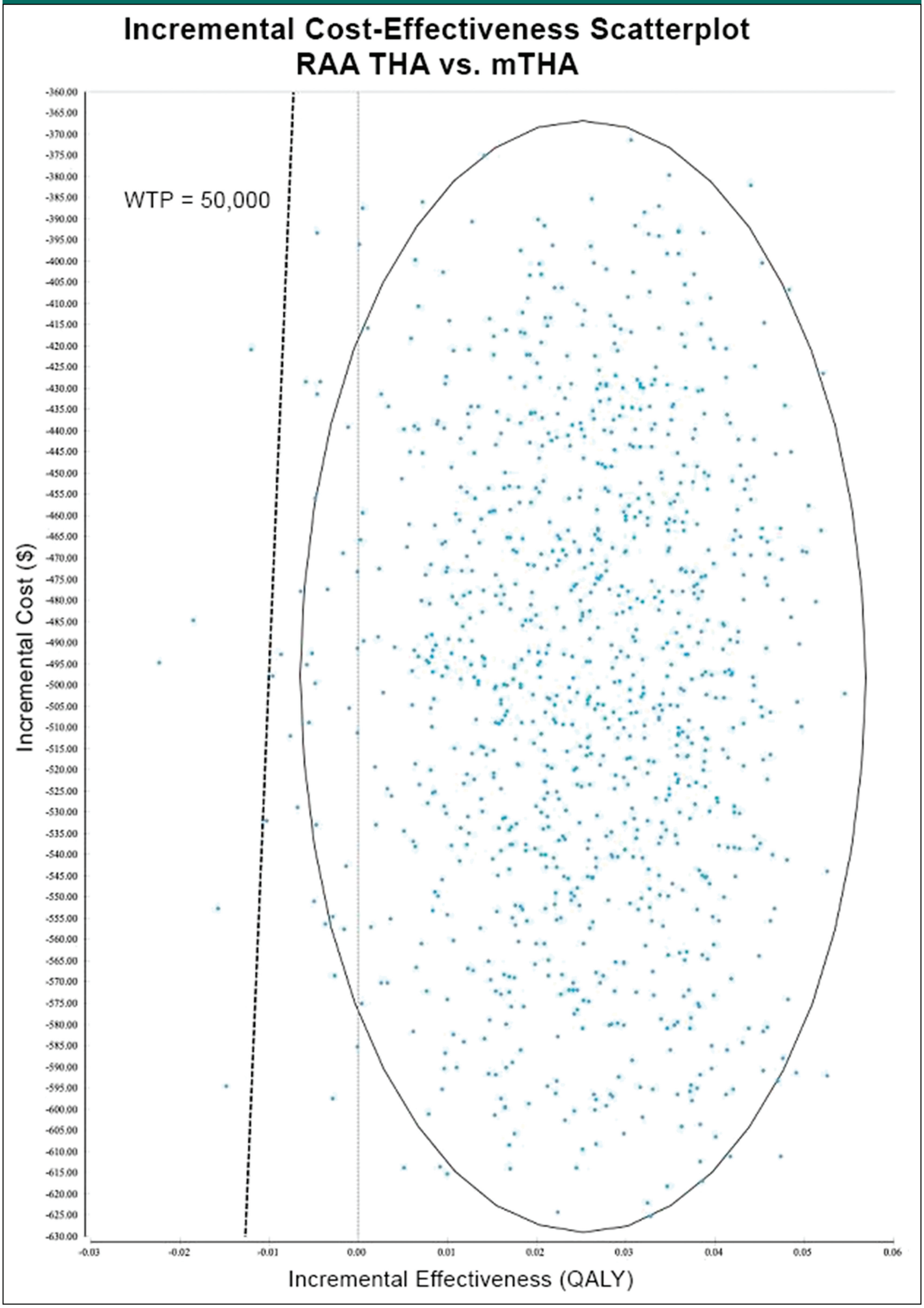
The results of the current study demonstrate that in the Medicare and private payer scenarios, RAA THA is more cost effective than conventional mTHA when considering direct medical costs from a payer's perspective. Medicare's cumulative cost difference at year five is $945, favoring RAA THA as a lower cost alternative. Similarly, private payer cost difference at year 5 is $1,810, supporting RAA THA as a lower cost alternative. RAA THA also generated more cumulative QALY, making it both less costly and more effective. This trend was persistent throughout the microsimulations, with RAA THA being cost effective in 99.4% of cases. To the author's knowledge, this study is one of the first cost analyses comparing RAA THA with mTHA from a payer's perspective, considering direct costs paid by Medicare and private payers for patients undergoing THA at a high-volume institution.

Our Markov model indicated notable cost effectiveness used by incorporating robotics relative to mTHA. This broadly aligns with evidence published in the unicompartmental knee arthroplasty (UKA) literature. RAA (UKA) had an ICER of $47,180 per QALY relative to manual UKA when cases exceed 94 annually and failure rates are less than 1.2% at 2 years. This estimate is below a conservatively determined willingness-to-pay threshold of $50,000 per QALY.[29] Likewise, the Markov decision analysis by Clement et al[30] determined that RAA UKA was a cost-effective alternative to mTKA and UKA regardless of surgical volume, producing an ICER ranging from £1,170 to £574 per QALY.

Sensitivity analyses conducted indicated that the initial utilities of mTHA and RAA THA were parameters that affected the preferred treatment strategy. We found that the initial utility of RAA THA was slightly higher than mTHA, which likely contributed markedly to RAA THA's cost effectiveness. Similar results have likewise been reported by Bukowski et al,[31] who concluded that RAA THA was associated with both markedly higher postoperative mHHS (92.1 ± 10.5 versus 86.1 ± 16.2) and notable changes in mHHS when (43.0 ± 18.8 versus 37.4 ± 18.3) compared with mTHA. Although the costs of infection and dislocation were not sensitive, sensitivity analyses indicated that they still had a large impact on the ICER. These results are similar to what has been reported in the literature, with most of the costs being associated with short-term events rather than long-term implant longevity. Shearer et al[32] found that most costs associated with THA occurred within the first few years.

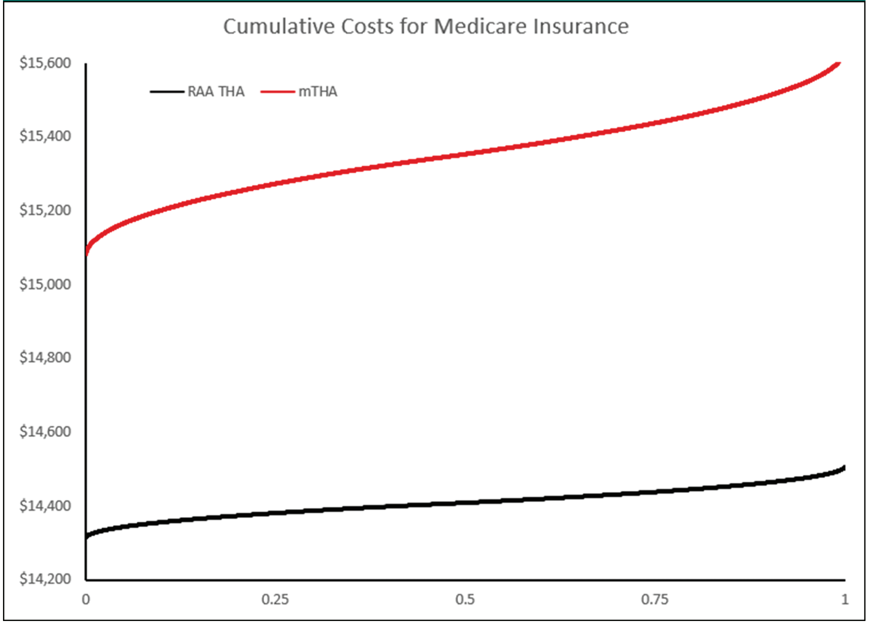
This analysis can help inform and provide supportive evidence for payer decisions to consider RAA THA as a

Figure 3



Incremental cost-effectiveness ratio (ICER) Scatter plot. Scatterplot of resulting ICER from 100,000 microsimulations showing individual patient variability. mTHA = manual total hip arthroplasty, RAA = robotic arm-assisted, THA = total hip arthroplasty

Figure 4



Graph showing the cumulative costs for Medicare. The values are derived from 100,000 simulations using a probabilistic sensitivity analysis. $ = 2019 US dollars, mTHA = manual total hip arthroplasty, RAA = robotic arm-assisted, THA = total hip arthroplasty

valid alternative. Our primary end point of the investigation was a direct medical cost comparison. To fully explore the RAA THA's value, financial benefits from each perspective should be considered using a variety of methods. Future studies should focus on the etiology of cost saving, investigating the magnitude of effects from complications, implant longevity, and hospital readmissions.

This study followed the recommendations from the Second Panel on Cost-Effectiveness in Health and Medicine to improve comparability and quality.[22,28] Nevertheless, our analysis has several limitations. As a note of caution, this empiric investigation provides quantitative data, which should be accepted as a theoretical approximation of complex reality and not held as a fact. Robotic system costs or benefits to a hospital were not included because it can be influenced by factors such as surgical volume,[29] efficiency gains,[33] reductions in the length of stay, and readmissions.[34] In addition, patient payers are not responsible for the upfront costs associated with acquiring the technology. Outcomes were derived from the literature and from our high-volume institution, which may have limited its generalizability. However, sensitivity analysis conducted and demonstrated that model conclusions can tolerate notable variation of variables. Thus, we believe that the objective findings are relevant to the payer when considering a primary THA patient cohort treated at a high-volume surgical center. Mid-term follow-up trends must be assessed for persistence over time, including longer duration of follow-up. However, previous economic analyses have indicated that 91% of reinterventions occurred within the first year,[19] and longer follow-up may not alter conclusions of this study. In addition, short-term complications were found to have more effect on the cost effectiveness of THA relative to implant longevity.[32,35] Finally, this study examined direct costs only. Indirect costs and their subsequent societal implications are salient points to consider.[36] The current study did not consider surgical time, cost of the robotic arm, or length of stay. Indirect costs cannot be inferred because of the paucity of literature, considering their estimates and impact.

Conclusion

In the Medicare and private payer scenarios, RAA THA is more cost effective than conventional mTHA when considering direct medical costs from a payer perspective.

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