Technology Review: CT Scan-Guided, 3-Dimensional, Robotic-Arm Assisted Lower Extremity Arthroplasty

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ABSTRACT

Robotic-arm assisted lower extremity arthroplasty using computed tomography scan (CT)-based 3-dimensional (3D) modeling operative technologies has increasingly become mainstream over the past decade with over 550,000 procedures performed between first use in 2006 and November 2021. Studies have demonstrated multiple advantages with these technologies, such as decreased postoperative pain and subsequent decreased narcotic usage, decreased lengths of stay, less complications, reduced damage to soft tissues, decreased readmissions, as well as economic advantages in the form of meaningful cost savings for payors. The purpose of this report was to clearly and concisely summarize the good-to-high methodology peer-reviewed, published literature regarding CT scan-based, 3-dimensional robotically-assisted unicompartmental knee arthroplasty, total knee arthroplasty, and total hip arthroplasty stratified by: (1) prospective randomized studies; (2) database comparison studies; (3) national registry studies; (4) health utility studies; (5) comparison studies; and (6) basic science studies. A literature search was conducted and, after applying inclusion criteria, each study was graded based on the modified Coleman methodology score ("excellent" 85–100, "good" 70–84, "fair" 55–69, "poor" <54 points). A total of 63 of 63 good-to-excellent methodology score reports were positive for this technology, including 11 that demonstrated decreased pain and/or opioid use when compared to traditional arthroplasty techniques. The summary results of these high-quality, peer-reviewed published studies demonstrated multiple advantages of this CT scan-based robotic-arm assisted platform for lower extremity arthroplasty.

INTRODUCTION

Common reasons for implant failure after lower extremity joint arthroplasty include loosening, instability, and malalignment, which can result from technical errors.[1] Robotic-arm assisted procedures have been gaining adoption, likely due to their potential to help reduce surgeon errors, to improve surgical planning, and to improve the accuracy of implant positioning.[2,3] The only contemporary robotic-arm assisted lower extremity arthroplasty system with medium- to long-term published data uses computed tomography scan (CT)-based 3-dimensional (3-D) modeling operative technologies in the treatment of pathologies, such as osteoarthritis and osteonecrosis.[4–6] Preoperative, patient-specific reconstructions of the joint anatomy are created with a CT scan and used to plan implant positioning by analyzing desired bone cuts, alignments, and kinematics through the arc of motion.[7,8] Intraoperatively, the robotic technology in question uses stereotactic windows that limit the action of the surgeon-controlled milling burr or saw and only allows for resection within a predefined haptic bone window. The surgical plan is created in an individually customized fashion with a high degree of accuracy, and the bone is cut precisely utilizing the robotic arm under the surgeon's control.[2,5,9–11] Theoretically, when compared to manual arthroplasty procedures, this haptic-based technology should help surgeons better protect the soft tissues and may allow for more precision as well as more rapid postoperative rehabilitation and recovery.[7,12]

There have been multiple clinical studies evaluating this technology's safety and efficacy including randomized controlled trials. CT scan guided 3-dimensional robotic-arm assisted surgeries have been found to be associated with improved accuracy in implant positioning and reduced outliers in limb alignment compared with conventional jig-based procedures.[2,9,13,14] Furthermore, proper soft-tissue tensioning and ligamentous balancing have been shown to further optimize patient functional outcomes.[15]

In this technology overview, we assessed the published, peer-reviewed literature that evaluated outcomes of CT scan-based robotic-assisted technologies compared to traditional arthroplasties used for unicompartmental knee arthroplasties (UKAs), total knee arthroplasties (TKAs), and total hip arthroplasties (THAs) in: (1) prospective randomized studies; (2) database comparison studies; (3) national registry studies; (4) health utility studies; (5) comparison studies; and (6) basic science studies.

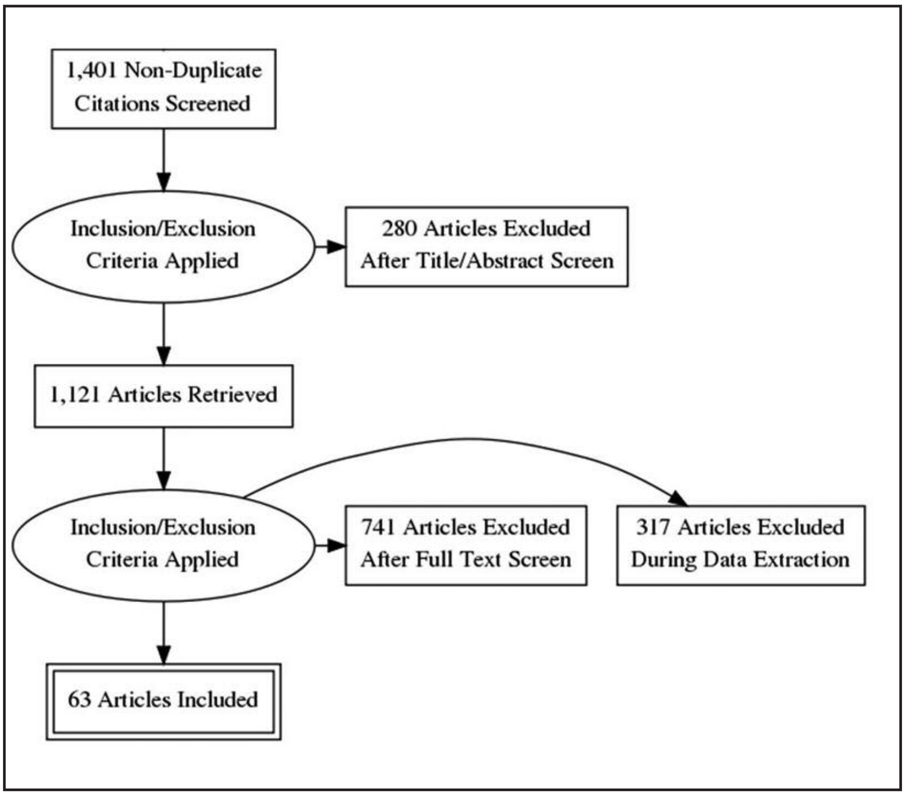

Figure 1. Strobe diagram for study selection.

MATERIALS AND METHODS

A search of the PubMed, EMBASE, and Cochrane Library completed between November 2, 2021 and November 3, 2021 specifically on the MAKO platform (Mako Surgical Corp., Weston, Florida) resulted in 63 reports after exclusion criteria were applied (Fig. 1). In this report, we separated these studies into prospective randomized, database comparison, national registry, health utility, comparison, and basic science study categories with some overlap (explained below). For the database comparison studies, those deemed eligible for inclusion were conducted after 2016 which is when the Mako Total Knee application was first released.[16] For example, a study by Naziri et al. was excluded because they tracked procedures from 2009 to 2016.[16] Comparison studies were defined as those with control groups and, thus, the majority were of Level 2 evidence.[17] Pearle et al. was excluded because they did not have a comparison group.[18]

Systematic reviews and meta-analyses were excluded in this updated report. Additionally, reports studying other robotic platforms were not evaluated, given the lack of publications or clinical experience with other orthopaedic robotic systems. Furthermore, reports comparing computer-navigation to these robotic-assisted technologies and those comparing two different robotic platforms were also excluded,[19,20] unless specifically compared to non-robotic procedures.[21] Studies comparing a robotic-assisted technique of one procedure versus a manual version of a different procedure, such as robotic UKA versus manual TKA,[22] or different prostheses manufacturers were also excluded.[23] Reports were required to have modified Coleman methodology scores of at least 70 points (see below), demonstrating a high-level, quality study.

Prospective randomized studies are Level 1 evidence.[17] The majority of the health utility, comparison, and basic sciences studies in the present report are Level 2 evidence (39 out of 49, 79.59%).[17] Database comparison and national registry studies are Level 3 evidence. Overall, in this report, there are five (7.94%) level of evidence (LOE) 1

Table I
Modified Coleman methodology scores

Study	Score	LOE	Study	Score	LOE
Prospective Randomized			Sultan et al. 2019[50]	77	2
Banger et al. 2021[38]	92	1	Banchetti et al. 2018[51]	84	2
Bell et al. 2017[80]	85	1	Clement et al. 2020[66]	84	2
Blyth et al. 2008[39]	89	1	Domb et al. 2020[33]	87	2
Gilmour et al. 2018[10]	89	1	Domb et al. 2014[53]	80	2
Kayani et al. 2021[14]	79	1	Elmallah et al. 2015[54]	80	2
Database			Hadley et al. 2020[65]	84	2
Bendich et al. 2021[21]	80	3	Illgen et al. 2017[11]	84	2
Cool et al. 2019[75]	84	3	Kolodychuk et al. 2021[63]	80	2
Emara et al. 2021[41]	90	3	Lawson et al. 2019[55]	80	2
Emara et al. 2021[40]	90	3	Nawabi et al. 2013[56]	75	2
Kirchner et al. 2021[76]	84	3	Perets et al. 2021[67]	84	2
Ofa et al. 2020[77]	84	3	Salem et al. 2020[34]	85	2
Vakharia et al. 2021[42]	90	3	Singh et al. 2021[64]	84	2
National Registry			Suarez-Ahedo et al. 2017[57]	80	2
Boylan et al. 2018[43]	90	3	Cool et al. 2019[75]	84	3
AOANJRR 2021[78]	87	3	Kayani et al. 201[97]	85	2
AOANJRR 2020[44]	84	3	Kleeblad et al. 2018[35]	90	2
Health Utility			MacCallum et al. 2016[58]	80	3
Cotter et al. 2020[25]	85	2	Archer et al. 2021[59]	80	3
Cool et al. 2019[26]	85	3	Kayani et al. 2019[60]	80	2
Maldonado et al. 2019[27]	87	3	Kayani et al. 2018[81]	82	2
Mont et al. 2021[28]	85	3	Kayani et al. 2018[12]	77	2
Pierce et al. 2020[29]	85	3	Mitchell et al. 2021[36]	89	2
Pierce et al. 2021[30]	85	3	Smith et al. 2021[82]	84	2
Cool et al. 2019[75]	84	3	Sodhi et al. 2020[37]	85	2
Emara et al. 2021[40]	90	3	Naziri et al. 2019[73]	77	2
Comparison			Bukowski et al. 2016[74]	84	3
Marchand et al. 2021[79]	84	2	Lonner et al. 2010[71]	77	2
Marchand et al. 2019[45]	84	2	Basic Science		
Marchand et al. 2017[46]	70	2	Hampp et al. 201[95]	70	2
Bhimani et al. 2020[47]	80	2	Hampp et al. 2021[70]	70	2
Malkani et al. 2019[31]	89	2	Khlopas et al. 2017[68]	75	2
Malkani et al. 2020[32]	89	2	Hampp et al. 2019[69]	75	2
Khlopas et al. 2020[48]	80	2	Citak et al. 2012[72]	70	2
Mahoney et al. 2020[49]	80	2			

LOE, level of evidence

reports, 39 (61.90%) LOE 2 reports, and 19 (30.16%) LOE 3 reports. After grading each paper using the modified Coleman methodology score, which assesses the quality of methodology (Table I), each study was further assessed and is described within the sections of this paper.[24] This rating scale measures sample sizes and follow-up times, as well as effectiveness of clinical measurements, and is often used to compare procedural investigations. The score ranges from 0 to 100 and studies are categorized as "excellent" (85 to 100), "good" (70 to 84), "fair" (55 to 69), and "poor" (<55) methodological quality, as reported by Cowen et al.[24] In the present report, grading according to the modified Coleman methodology score method yielded: 23 (36.51%) "excellent"[7,9,10,25–44] and 40 (63.49%) "good"[5,11,12,14,21,45–79] quality studies. Only "excellent" and "good" quality studies were included for analyses.

In assessing the literature, we found 63 reports concerning CT scan-based robotically-assisted total joint arthroplasty, total knee arthroplasty (n=29), total hip arthroplasty (n=21), and unicompartmental knee arthroplasty (n=15) (one study[43] evaluated all three) that had to do with its efficacy. These included five prospective randomized trials, 37 high-level comparison studies, 10 database and registry studies, eight health utility studies, and five basic science randomized studies (one study[40] was both a database as well as a health utility report and one study[75] was both a comparison as well as a health utility report).

PROSPECTIVE RANDOMISED STUDIES

There were five papers from prospectively randomized patient cohorts.[10,14,38,39,80] Grading using the modified Coleman methodology score yielded: four "excellent"[10,38,39,80] papers and one "good"[14] quality paper. Four out of the five papers studied unicompartmental knee arthroplasties (UKAs),[10,38,39,80] while the other investigated total knee arthroplasties

Table II
Results of prospective randomized studies

Report	Subjects	Results
Bell et al. 2017[80]	120	Accuracy of component positioning improved with use of CT scan-based robotic-assisted UKA procedure with significantly lower median errors in all component parameters ($p < 0.01$)
Blyth et al. 2008[39]	139	Pain scores for CT scan-based robotic-arm assisted UKA group 55.4% lower than those in manual group ($p = 0.040$)
Gilmour et al. 2018[10]	139	American Knee Society Score 193.5 for CT scan robotic-arm assisted UKA group and 174.0 for manual group at two years ($p = 0.017$)
Banger et al. 2021[38]	104	Lower reintervention rate in CT scan-based robotic-arm assisted UKA group with 0% requiring further surgery compared with six (9%) of the manual group requiring additional surgical intervention ($p < 0.001$)
Kayani et al. 2021[14]	30	CT scan-based robotic-arm assisted TKA associated with significantly improved preservation of periarticular soft tissue envelope ($p < 0.001$) and reduced femoral ($p = 0.012$) as well as tibial ($p = 0.023$) bone trauma compared with conventional TKA

UKA, unicompartmental knee arthroplasty; TKA, total knee arthroplasty

(TKA).[14]

All of the reports demonstrated improved clinical results for CT scan-based robotic-arm assisted knee arthroplasties when compared to their comparison group (Table II).[10,14,38,39,80] Bell et al. demonstrated that the accuracy of component positioning was improved with CT scan-based robotic assistance with significantly lower median errors in all component parameters ($p<0.01$).[80] Importantly, more patients who underwent robotic-assisted unicompartmental knee arthroplasty had component implantation position within 2° of the target position compared with the group who underwent conventional unicompartmental knee arthroplasty before femoral component sagittal position (57 vs. 26%, $p=0.0008$), femoral component coronal position (70 vs. 28%, $p=0.0001$), femoral component axial position (53 vs. 31%, $p=0.0163$), tibial component sagittal position (80 vs. 22%, $p=0.0001$), and tibial component axial position (48 vs. 19%, $p=0.0009$). Gilmour et al. demonstrated greater survivorship in their robotic-arm assisted UKA group when compared to a manual group (100 vs. 96.3%).[10] Furthermore, a greater proportion of their robotic-assisted group was "pain free" at two years (29.3 vs. 15.7%). Banger et al. found lower reintervention rates in the robotic-arm assisted UKA group with none requiring further surgery compared with six (9%) in the manual group ($p<0.001$).[38] Kayani et al. found that robotic-arm assisted TKAs had significantly reduced levels of interleukin-6 ($p<0.001$), tumor necrosis factor-α ($p=0.021$), erythrocyte sedimentation rate (ESR) ($p=0.001$), C-reactive protein (CRP) ($p=0.004$), lactate dehydrogenase ($p=0.007$), and creatine kinase ($p=0.004$) at postoperative day seven compared with conventional TKA.[14] Additionally, robotic-assisted TKA was associated with significantly improved preservation of the periarticular soft tissue envelope ($p<0.001$) and reduced femoral ($p=0.012$) as well as tibial ($p=0.023$) bone trauma. Furthermore, CT scan-based robotic-arm assisted TKA significantly improved the accuracy of limb alignment ($p<0.001$), femoral component positioning ($p<0.001$), and tibial component positioning ($p<0.001$).[14] Blyth et al. explored the early clinical outcomes comparing robotic-arm assisted UKA with manual UKA performed using traditional surgical jigs.[39] They showed that while the preoperative pain levels were not different between the two groups, during the first postoperative day through the first week postoperatively, the median pain scores for the robotic-arm assisted group were 55.4% lower than those observed in the manual surgery group ($p=0.040$).

DATABASE COMPARISON STUDIES

A total of seven papers were database comparison studies.[21,40–42,75–77] Grading using the modified Coleman methodology score yielded: three "excellent"[40–42] and four "good"[21,75–77] quality studies. Three[21,40,77] of the studies investigated TKAs, while the remaining (two each) analyzed either UKAs[42,75] or total hip arthroplasties (THAs).[41,76] All of the reports (seven out of seven, 100%) demonstrated improved clinical results for CT scan-based robotic-arm assisted knee arthroplasties when compared to their comparison group (Table III).[21,40–42,75–77] These results included lower complication rates, fewer revisions, shorter lengths of stay (LOS), lower costs, or decreased rates of manipulations under anesthesia (MUAs). Ofa et al. demonstrated that when compared to non-robotic TKA patients, CT scan-based robotic-assisted TKA patients had lower rates of prosthetic revision at one year after discharge ($p<0.05$) and lower rates of manipulations under anesthesia at 90 days as well as one year after discharge ($p<0.05$).[77] Additionally, this cohort had fewer occurrences of deep vein thromboses, altered mental statuses, pulmonary emboli, anemiae, acute renal failures, cerebrovascular events, pneumoniae, respiratory failures, and urinary tract infections during their inpatient hospital stays (all $p<0.05$) and at 90 days after discharge (all $p<0.05$). Furthermore, patients in the robotic-assisted cohort had lower levels of mean morphine milligram equivalents consumption at all time periods measured (90 days: 873 vs. 1,150, $p<0.001$; six months: 1,837 vs. 2,898, $p<0.001$; and one year: 3,578 vs. 6,203, $p<0.001$).

Table III
Results of database comparison studies

Report	Subjects	Results
Bendich et al. 2021[21]	1,307,411	CT scan-based robotic-assisted TKA had significantly lower odds of all-cause 90-day complications requiring readmission than conventional TKA (odds ratio 0.68; 97.5% confidence interval 0.56 to 0.83, $p < 0.001$)
Cool et al. 2019[75]	738	Patients who underwent CT scan-based robotic-assisted UKA had fewer revision procedures ($p = 0.002$) as well as lower lengths of stay at index and index costs ($p = 0.0047$) than manual UKA patients
Emara et al. 2021[41]	4,699,894	Implant-related mechanical complications were lower in CT scan-based robotic-assisted THA (0.5 vs. 3.1%; $p < 0.001$) compared to manual THA and was associated with significantly lower in-hospital dislocation (0.1 vs. 0.8%; $p < 0.001$)
Emara et al. 2021[40]	7,337,762	CT scan-based robotic-assisted knee arthroplasty exhibited shorter LOS ($p < 0.001$), lower in-hospital implant-related mechanical complications ($p < 0.05$), and lower in-hospital procedure-related non-mechanical complications ($p = 0.005$) than manual knee arthroplasty
Kirchner et al. 2021[76]	1,516	Mean LOS for CT scan-based robotic-assisted THA was 2.69 + 1.25 days compared with 2.82 + 1.18 days for conventional THA ($p < 0.001$)
Ofa et al. 2020[77]	755,350	Patients in manual TKA cohort had higher levels of prosthetic revision at one year after discharge ($p < 0.05$), higher manipulations under anesthesia at 90 days and one year after discharge ($p < 0.05$), and higher levels of mean morphine milligram equivalents consumption at all time periods measured ($p < 0.001$)
Vakharia et al. 2021[42]	35,061	CT scan-based robotic-assisted UKA procedures had significantly lower revision incidence (0.99 vs. 4.24%, $p = 0.003$) and revision burden (0.91 vs. 4.23%, $p = 0.005$) compared with manual UKAs

TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty; THA, total hip arthroplasty LOS, length of stay

NATIONAL REGISTRY STUDIES

Three reports were registry studies[43,44,78] with two “excellent”[43,78] and one “good”[44] modified Coleman methodology score. All three reports showed improved outcomes with the CT scan-based robotically-assisted cases versus standard arthroplasty techniques (Table IV).

Boylan et al. examined UKAs, TKAs, as well as THAs, while two Australian Orthopaedic Association National Joint Replacement Registry (AOANJRR) reports investigated UKAs.[43,44,78] Additionally, Boylan et al. were interested in utilization trends, while the remaining reports demonstrated improved survivorship compared to manual for robotically-assisted UKAs.[43,44,78] The AOANJRR 2020 annual report showed that CT scan-based robotically-assisted UKAs showed lower overall revision rates compared to non-robotically assisted procedures (2.8 vs. 3.6%) at three years.[44] Furthermore, the AOANJRR 2021 annual report demonstrated lower overall revision rates continuing through five years (4.2 vs. 4.7%).[78] Additionally, CT scan-based robotically-assisted UKAs had a lower interquartile range than other non-robotically assisted UKAs (3.4 to 5.0 vs. 4.2 to 5.2).[78]

Table IV
Results of national registry studies

Report	Subjects	Results
Boylan et al. 2018[43]	321,522	Proportion using technology assistance (knees as well as hips) grew each year ($p < 0.001$) and proportion of hospitals as well as surgeons using robotic assistance also increased ($p < 0.001$ for both)
AOANJRR 2020[44]	60,387	CT scan-based robotically-assisted UKAs had lower overall revision rates compared to non-robotically assisted procedures (2.8 vs. 3.6%) at three years
AOANJRR 2021[78]	44,757	CT scan-based robotically-assisted UKAs had lower overall revision rates compared to non-robotically assisted procedures (4.2 vs. 4.7%) at five years

AOANJRR, Australian Orthopaedic Association National Joint Replacement Registry; UKA, unicompartmental knee arthroplasty

Table V
Results of health utility studies

Report	Subjects	Results
Cotter et al. 2020[25]	286	Inpatient costs were lower ($p < 0.001$), LOS was reduced ($p < 0.0001$), prescribed opioids were reduced ($p < 0.0001$), and 90-day episode-of-care (EOC) costs were lower for CT scan-based robotic-assisted TKA compared with manual TKA ($p < 0.001$)
Cool et al. 2019[26]	3,114	Overall 90-day EOC costs were less for CT scan-based robotic TKA ($p < 0.0001$)
Maldonado et al. 2019[27]	N/A	Markov model demonstrated that CT scan-based robotic-arm assisted THA had cost savings with mean differential of $945 for Medicare and $1,810 for private insurance relative to manual THA while generating slightly more utility (0.04 quality-adjusted life year)
Mont et al. 2021[28]	3,114	Mean total episode payment was less at 30 days, 60 days, and 90 days ($p < 0.0001$) when comparing CT scan-based robotic-assisted to manual TKA
Pierce et al. 2020[29]	2,142	Overall post-surgery expenditures were $1,332 less in the CT scan-based robotic-assisted TKA arm ($p = 0.0018$) and 90-day global expenditures (index plus post-surgery) were $4,049 less ($p < 0.0001$)
Pierce et al. 2021[30]	5,608	Total 90-day EOC costs for CT scan-based robotic-assisted THA patients were US $785 less than manual ($p = 0.0095$)
Cool et al. 2019[75]	492	Demonstrated savings of $1,914 over 24 months for CT scan-based robotic-assisted UKA versus manual
Emara et al. 2021[40]	7,337,762	CT scan-based robotic-assisted knee arthroplasty exhibited lower in-hospital costs ($p < 0.001$) than manual knee arthroplasty

EOC, episode-of-care; TKA, total knee arthroplasty; N/A, not applicable; THA, total hip arthroplasty

HEALTH UTILITY STUDIES

There were eight health utility studies,[25–30,40,75] which all scored "excellent" according to the modified Coleman methodology. Five out of eight analyzed TKAs,[25,26,28,29,40] while two investigated THAs,[27,30] and one studied UKAs. All demonstrated reduced episode-of-care costs for robotic-assisted lower extremity arthroplasties (Table V).

Cotter et al. found that inpatient costs were lower when comparing CT scan-based robotic-assisted and manual TKA ($3,894 vs. $5,587, respectively, $p<0.001$).[25] Additionally, as well as consistent with other studies previously discussed above, prescribed opioids were reduced 57% (984.2 vs. 2,240.4 morphine milligram equivalents, respectively, $p<0.0001$) and 90-day episode-of-care costs were $2,091 less ($15,630 vs. 17,721, respectively; $p<0.001$) in the robotic-arm assisted cohort. Mont et al. demonstrated that CT scan-based robotic-assisted TKAs had lower mean total episode payments than manual TKAs at 30 days ($17,768 vs. $19,899, $p<0.0001$), 60 days ($18,174 vs. $20,492, $p<0.0001$), and 90 days ($18,568 vs. $20,960, $p<0.0001$).[28] Additionally, robotic-assisted patients had lower skilled nursing facility costs at 30 days ($6,416 vs. $7,732, $p=0.0040$), 60 days ($6,678 vs. $7,901, $p=0.0072$), and 90 days ($7,201 vs. $7,947, $p=0.0230$). There were two reports with results only on in-hospital costs, which are expectedly higher with new technologies.[41,76] However, they did not report on 30-, 60-, or 90-day episode-of-care costs.

COMPARISON STUDIES

These analyses included 37 comparison studies with control groups.[7,11,12,31–37,45–51,53–67,71,73–75,79,81,82] Grading using the modified Coleman methodology score yielded: eight (21.62%) "excellent"[7,31–37] and 29 (75.68%) "good"[11,12,45–67,71,73–75,79] scores. There were 17 studies that investigated TKAs,[12,31,32,36,37,45–50,59–62,73,79] while 15 analyzed THAs,[11,33,34,51,53–57,63–67,74] and five studied UKAs.[7,35,58,71] All of the reports (37 out of 37, 100%) demonstrated enhanced results for CT scan-based robotic knee arthroplasties when compared to their comparison groups (Table VI).[7,11,12,31–37,45–51,53–67,71,73–75,79]

Multiple comparison studies have demonstrated significantly improved pain, physical function, and total Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores for CT scan-based robotic-assisted TKAs through two years when compared to manual TKAs.[45,46,79] Malkani et al. found that the overall manipulation under anesthesia rate for robotic-assisted TKAs was lower (two out of 188, 1.06%) than manual TKAs (nine out of 188, 4.79%) ($p=0.032$).[31] Improved patient-reported outcome measures were corroborated by multicenter studies.[48,49,83] Similar results were found for robotic-assisted THAs as Domb et al. demonstrated significantly higher Harris Hip Scores, Forgotten Joint Scores-12, Veterans RAND-12 Physical, and 12-Item Short Form Survey Physical Scores ($p<0.001$, $p=0.002$, $p=0.002$, $p=0.001$, respectively) when compared to manual THAs.[33] Cool et al. found that patients who underwent CT scan-based robotic-assisted UKAs had fewer revision procedures (0.81 vs. 5.28%; $p=0.002$), shorter mean LOS (2.00 vs. 2.33 days),

Table VI
Results of comparison studies

Report	Subjects	Results
Marchand et al. 2021[79]	160	Patients in CT scan-based robotic-assisted cohort had significantly improved two-year postoperative reduced Western Ontario and McMaster Universities Osteoarthritis Index (r-WOMAC) mean pain ($p = 0.02$), physical function ($p = 0.009$), and total scores ($p = 0.009$) compared with the manual TKA
Marchand et al. 2019[45]	106	CT scan-based robotic-arm assisted TKA cohort had significantly improved mean total ($p = 0.03$) and physical function WOMAC scores ($p = 0.02$) when compared with the manual cohort
Marchand et al. 2017[46]	40	Mean WOMAC pain score, standard deviation (SD), and range for the manual and CT scan-based robotic TKA cohorts were 5 + 3 (range: 0 to 10) and 3 + 3 (range: 0 to 8, $p < 0.05$), respectively
Bhimani et al. 2020[47]	267	At six-week interval, CT scan-based robotic-assisted TKA group had lower visual analog scale (VAS) pain scores with rest ($p = 0.03$) as well as activity ($p = 0.02$) and required 3.2mg less morphine equivalents per day relative to the conventional group ($p < 0.001$)
Malkani et al. 2019[31]	376	Overall manipulation under anesthesia rate for CT scan-based robotic-assisted cohort was 1.06% (2/188 patients), while it was 4.79% in control cohort (9/188) ($p = 0.032$)
Malkani et al. 2020[32]	188	All patients who underwent CT scan-based robotic-assisted TKA reported excellent postoperative outcomes for the Short Form-12 Questionnaire (SF-12), Forgotten Joint Score (FJS), and Knee Society total and subscores (KSS)
Khlopas et al.[48]	252	At four to six weeks postoperatively, CT scan-based robotic-assisted TKA patients were found to have significantly larger improvements in walking and standing ($p = 0.019$)
Mahoney et al. 2020[49]	229	CT scan-based robotic-assisted TKA demonstrated greater accuracy to plan for tibial component alignment ($p < 0.001$), femoral component rotation ($p = 0.015$), and tibial slope (2.9 [1.5, 5.0] vs. 1.1° [0.6, 2.0]. $p < 0.001$)
Sultan et al. 2019[50]	82	Mean postoperative posterior condylar offset ratio (PCOR) was larger in manual TKA when compared to the CT scan-based robotic-assisted cohort (0.53 vs. 0.49; $p = 0.024$)
Banchetti et al. 2018[51]	220	Significant difference in length of hospital stay between the CT scan-based robotic-assisted group and standard group ($p < 0.001$)
Clement et al. 2020[66] 2021[66]	120	CT scan-based robotic-assisted THA cohort associated with overall greater rate of component positioning in Lewinnek and Callanan safe zones ($p \leq 0.003$) and restoration of leg length ($p < 0.001$)
Domb et al. 2020[33]	132	CT scan-based robotic THA group reported significantly higher Harris Hip Score, Forgotten Joint Score-12, Veterans RAND-12 Physical, and 12-Item Short Form Survey Physical ($p < 0.001$, $p = 0.002$, $p = 0.002$, $p = 0.001$, respectively)
Domb et al. 2014[53]	160	One hundred percent (50/50) of the CT scan-based robotic-assisted THAs were within Lewinnek safe zone compared with 80% (40/50) of the conventional THAs ($p = 0.001$)
Elmallah et al. 2015[54]	224	A total of 99% of CT scan-based robotic-arm assisted THA patients remained within the pre-designated safe zone showing improved accuracy when compared to conventional surgery
Hadley et al. 2020[65]	232	Patients in CT scan-based robotic-assisted THA cohort had significantly higher WOMAC ($p < 0.001$) and Harris Hip Scores ($p < 0.05$) compared to the conventional THA cohort at final follow-up

Table VI (continued)
Results of comparison studies

Report	Subjects	Results
Illgen et al. 2017[11]	300	Rate of acetabular component placement within Lewinnek safe zone highest in CT scan-based robotic-assisted THA cohort compared to manual THAs ($p < 0.001$)
Kolodychuk et al. 2021[63]	120	CT scan-based robotic-arm assisted technology allowed a newly-trained surgeon to produce similarly accurate results and outcomes as experienced surgeons in traditional anterior and posterior hip arthroplasty
Lawson et al. 2019[55]	100	Statistically significant improvement in number of acetabular components placed within 5° of target alignment with use of CT scan-based robotic-assisted guidance compared to manual technique ($p = 0.0142$)
Nawabi et al. 2013[56]	12	Error for manual implantation compared to CT scan-based robotic-assisted THA was five times higher for cup inclination and 3.4 times higher for cup anteversion ($p < 0.01$) when compared to manual implantation
Perets et al. 2021[67]	170	Both Harris Hip Score (HHS) and FJS-12 were significantly higher in the CT scan-based robotic-arm assisted group at minimum two-year follow-up compared to manual THA
Salem et al. 2020[34]	26 studies	CT scans found to be more accurate than radiographs in predicting implant size as well as alignment preoperatively and provide improved visualization of extraarticular deformities when planning a THA
Singh et al. 2021[64]	1,960	Lengths of stay was statistically longer for patients who underwent conventionally performed THA versus CT scan-based robotically-assisted THAs ($p < 0.001$)
Suarez-Ahedo et al. 2017[57]	114	Difference between cup diameter and femoral head diameter significantly lower in CT scan-based robotically-assisted THA group ($p < 0.02$) compared to conventional THA
Cool et al. 2019[75]	492	At 24 months after the primary UKA procedure, patients who underwent CT scan-based robotically-assisted UKA had fewer revision procedures ($p = 0.002$) than manual UKA patients. Length of stay at index was also lower ($p = 0.0047$)
Kayani et al. 2019[7]	146	CT scan-based robotic-arm assisted UKA associated with reduced postoperative pain ($p < 0.001$), decreased opiate analgesia requirements ($p < 0.001$), shorter time to straight leg raise ($p < 0.001$), decreased number of physiotherapy sessions ($p < 0.001$), and increased maximum knee flexion at discharge ($p < 0.001$) compared with conventional jig-based UKA
Kleeblad et al. 2018[35]	473	CT scan-based robotic-arm assisted medial UKA showed high survivorship and satisfaction at mid-term follow-up compared to previous reports of manual medial UKA
MacCallum et al. 2016[58]	510	Coronal baseplate positioning was more accurate to plan for CT scan-based robotic-arm assisted UKA ($p < 0.\ 0001$) and was more precise ($p < 0.0001$)
Archer et al. 2021[59]	10,296	Mean LOS significantly lower in CT scan-based robotic-assisted compared with manual TKA procedures ($p < 0.00001$). Proportion discharged home significantly higher for patients who underwent CT scan-based robotic-assisted compared with manual TKAs ($p < 0.00001$)
Kayani et al. 2019[60]	120	CT scan-based robotic TKA improved accuracy of implant positioning ($p < 0.001$) and limb alignment ($p < 0.001$) with no additional risk of postoperative complications compared to conventional manual TKA
Kayani et al. 2018[81]	80	CT scan-based robotic-arm assisted TKA associated with reduced postoperative pain ($p < 0.001$), decreased analgesia requirements ($p < 0.001$), decreased reduction in postoperative hemoglobin levels ($p < 0.001$), shorter time to straight leg raise ($p < 0.001$), decreased number of physiotherapy sessions ($p < 0.001$), and improved maximum knee flexion at discharge ($p < 0.001$) compared with conventional jig-based TKA

Table VI (continued)
Results of comparison studies

Report	Subjects	Results
Kayani et al. 2018[12]	60	Patients who underwent CT scan-based robotic-assisted TKA had reduced medial soft tissue injury in both passively correctible (p < 0.05) and non-correctible varus deformities (p < 0.05), more pristine femoral (p < 0.05) as well as tibial (p < 0.05) bone resection cuts, and improved macroscopic soft tissue injury (MASTI) scores compared to conventional TKA (p < 0.05)
Mitchell et al. 2021[36]	287	Manual TKA patients required longer LOS (p < 0.001), greater morphine milligram equivalents consumption (p = 0.02), and increased physical therapy (PT) visits with increased 30-day readmission rates (p < 0.004) when compared with CT scan-based robotic-assisted TKA patients
Smith et al. 2021[82]	223	Likert scoring system demonstrated 94% of patients in the CT scan-based robotic-assisted group were either very satisfied or satisfied versus 82% in manual instruments TKA group (p = 0.005)
Sodhi et al. 2020[37]	63 studies	CT scans shown to 99% accurately predict prosthetic sizes preoperatively and better visualize surrounding anatomy, such as posterior cruciate ligament, compared with X-ray imaging
Naziri et al. 2019[73]	80	LOS was longer for traditional TKA compared to CT scan-based robotic-assisted TKA (1.92 vs. 1.27 days, p < 0.0001) and robotic-assisted TKA patients had improved 90-day ROM (+3.8° vs. -8.7°, p < 0.05)
Bukowski et al. 2016[74]	200	Difference between pre- and postoperative modified Harris Hip Score (mHHS) scores was statistically significant when comparing CT scan-based robotic-assistance with manual THA (43.0 ± 18.8 vs. 37.4 ± 18.3, p = 0.035)
Lonner et al. 2010[71]	58	Variance using manual instruments 2.6 times greater than CT scan-based robotically-assisted procedures

r-WOMAC, reduced Western Ontario and McMaster Universities Osteoarthritis Index; TKA, total knee arthroplasty; SD, standard deviation; VAS, visual analog scale; SF-12, Short Form-12 Questionnaire; FJS, Forgotten Joint Score; KSS, Knee Society total and subscores; PCOR, posterior condylar offset ratio; THA, total hip arthroplasty; HHS, Harris Hip Score; CT, computed tomography; LOS, length of stay; MASTI, macroscopic soft tissue injury; PT, physical therapy; ROM, range of motion; mHHS, modified Harris Hip Score

and incurred lower mean costs for the index stay plus revisions ($26,001 vs. $27,915) than manual UKAs at 24 months.[75] Bhimani et al. sought to determine the potential early clinical benefit of CT scan-based robotic-assisted TKA.[47] Specifically, they investigated the potential differences in visual analogue scores (VAS) for pain at rest and with activity as well as postoperative opiate usage when comparing the robotic and conventional TKA groups. They found that patients who underwent robotic-assisted TKA had significantly lower mean VAS pain scores at rest (p=0.001) and with activity (p=0.03) at two weeks postoperatively. At the six-week follow-up, this group continued to have significantly lower VAS pain scores with rest (p=0.03) and with activity (p=0.02). Furthermore, robotic-assisted TKA patients required 3.2mg less morphine equivalents per day relative to the conventional group (p<0.001). Additionally, at six weeks, a significantly greater number of patients in the CT scan-based robotic-arm assisted TKA group were free of opioid use compared to the conventional TKA group (70.7 vs. 57.0%, p=0.02). Kayani et al. also compared early postoperative functional outcomes between CT scan-based robotic-arm assisted TKA and conventional jig-based TKA.[81] Their results demonstrated that patients who underwent CT scan-based robotic-arm assisted surgery had significantly reduced pain scores at every postoperative time interval studied following surgery compared with conventional jig-based surgery (p<0.001). Furthermore, opiate analgesia requirements were also significantly reduced at all time points in the robotic cohort compared with the conventional group (p<0.001).

BASIC SCIENCE STUDIES

There were five randomized basic science studies that had “good” modified Coleman methodology scores.[5,68–70,72] All but one (UKAs)[72] of the reports examined TKAs and all found better results for CT scan-based robotic-assisted surgeries versus their comparison groups (Table VII).

Hampp et al. found that CT scan-based robotic-assisted TKA bone cuts were as or more accurate to plan-based on nominal median values in 11 out of 12 measurements when compared to manual TKAs.[5] Additionally, the final component positions were as or more accurate to plan-based on median values in all five measurements and were more precise to plan in four out of five measurements (p≤0.05). Furthermore, stacked error results from all cuts and implant positions for each specimen in

Table VII
Results of basic science studies

Report	Subjects	Results
Hampp et al. 201[95]	12	CT scan-based robotic-assisted TKA bone cuts were as or more accurate to plan than manual in 11 out of 12 measurements. Robotic-assisted TKA bone cuts were more precise to plan in eight out of 12 measurements ($p \le 0.05$). Robotic-assisted TKA final component positions were more precise to plan in four out of five measurements ($p \le 0.05$)
Hampp et al. 2021[70]	24	All CT scan-based robotic UKA subgroups had lower total trauma grading ($p < 0.01$), lower posterior capsular damage ($p < 0.01$), and less severe anterior cruciate ligament damage ($p < 0.01$) when compared to manual UKA
Khlopas et al. 2017[68]	13	For all CT scan-based robotic-assisted TKA cases, there was no visible evidence of disruption of any of the ligaments
Hampp et al. 2019[69]	12	Significantly less damage occurred to the posterior cruciate ligaments in CT scan-based robotic-assisted TKA versus the manual TKA specimens ($p < 0.001$)
Citak et al. 2012[72]	12	Surgical root mean square (RMS) errors for femoral component placement within 1.9mm and 3.7° in all directions of planned implant position for the CT scan-based robotic group, compared to only within 5.4mm and 10.2° for manual group. Mean RMS errors for tibial component placement within 1.4mm and 5.0° in all directions for robotic group; compared to only within 5.7mm and 19.2° for manual group

TKA, total knee arthroplasty; UKA, unicompartmental knee arthroplasty; RMS, root mean square

procedural order demonstrated that CT scan-based robotically-assisted TKA errors were less compared to manual. Khlopas et al. found that for all CT scan-based robotic-assisted TKAs, there was no visible evidence of disruption of any of the ligaments, but there was slight disruption noted of the posterior cruciate ligament (PCL) in two of the seven manual TKA cases.[68] Additionally, tibial subluxation and patella eversion were not required for visualization in any robotic-assisted TKA cases, but all manual TKA cases required tibial subluxation and patellar eversion to achieve optimal visualization. Hampp et al. also demonstrated that significantly less damage occurred to the PCLs of CT scan-based robotic-assisted versus manual TKAs ($p<0.001$).[69]

CONCLUSION

The CT scan-based robotic-arm assisted system in question has been in clinical use for unicompartmental knee arthroplasties as well as total hip arthroplasties for over a decade and for over five years for total knee arthroplasties. Over 550,000 procedures have been performed with this system between first use in 2006 and November 2021. All excellent and good methodological quality studies (63 out of 63, 100%) showed favorable results of the CT scan-based robotic-arm assisted procedures compared to matching groups, such as decreased lengths of stays, decreased complications, and cost savings over episodes of care. Furthermore, current evidence has shown advantages of CT scan-based, robotic-arm assisted TKA in mechanical knee alignment, implant positioning, ligamentous balance, and soft tissue protection. All of the studies in this analysis that investigated pain ($n=11$) and, more specifically, opioid usage ($n=6$) consistently demonstrated decreased narcotic requirements for patients who underwent CT scan-based, robotically-assisted lower extremity arthroplasties at all studied timepoints. Thus, the high-quality (defined for this analysis as "excellent" or "good" modified Coleman methodology scores) publications reviewed in connection with this report, which compared CT scan-based, robotic-arm assisted lower extremity arthroplasty to traditional techniques, demonstrated a number of clinical and economic benefits, including decreased LOS, better outcomes scores, and decreased pain and narcotic use.

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