

## Not All Robotic-assisted Total Knee Arthroplasty Are the Same

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*J Am Acad Orthop Surg* 2021;29:45-59

DOI: 10.5435/JAAOS-D-20-00654

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### ABSTRACT

Because value in healthcare has shifted to a measurement of quality relative to the cost, a greater emphasis exists on improving clinical and functional outcomes and patient satisfaction. Despite advances in implant design, surgical technique, and postoperative rehabilitation, multiple studies demonstrate that nearly 20% of patients remain dissatisfied with their overall outcomes after primary total knee arthroplasty (TKA). Because implant positioning, alignment, and equal soft-tissue balance are critical for a successful TKA, malalignment in the coronal, sagittal, and rotational planes continue to increase failure rates and cause poor clinical outcomes. Robotic-assisted TKA has gained momentum within the past 10 years to better control surgical variables by mitigating technical errors caused by insecure cutting guides and imprecise bone cuts. Contemporary robotic platforms have evolved along with our ability to collect high-quality patient-reported outcome measures data, and this combination is proving the clinical effectiveness. This comprehensive review investigates the advent of robotic-assisted TKA including advantages, disadvantages, historical, and commercially available newer generation systems, clinical outcomes, and cost analysis to better understand the potential added value of this technology.

**R**ecent healthcare policy efforts in the United States have focused on improving the value of primary total joint arthroplasty (TJA) by rewarding efficiency and quality of care outcomes relative to cost.<sup>1</sup> This is especially relevant for total knee arthroplasty (TKA), given the substantial financial burden on the healthcare system with anticipated logarithmic growth over the next 10 years.<sup>2</sup> The improved long-term survival and patient-reported outcomes related to pain, function, quality of life, and satisfaction after TKA are therefore becoming the benchmarks for understanding procedural quality and value by which treatment success is measured.

Technology-assisted TKA, such as computer-assisted navigation (CAN), has focused on surgical technique improvement to further improve outcomes by improving overall limb alignment and provide objective data to assist in

conventional guide placement for bony cuts.<sup>3</sup> Computer-assisted gap balancing and intraoperative tibial sensors have also been developed to improve on the limitations of both conventional measured resection and gap balancing by attempting to improve the accuracy of bony resection, implant and limb alignment, intercompartmental joint loading, soft-tissue tension, and balanced flexion and extension gaps.<sup>3</sup> Similarly, robotic technology has permeated the medical field recently in hope of improved surgical precision, procedure reproducibility, and measurable clinical outcomes.<sup>4</sup>

Robots, unlike CAN and computer-assisted gap balancing, enhance the human surgical experience with the ability to semiautonomously execute preoperative plans accurately and repeat tasks endlessly and consistently, whereas minimizing variation and maximizing reliability. Robotic-assisted TKA (RA-TKA) has similarly gained momentum within the past 10 years by mitigating technical errors caused by insecure cutting guides and imprecise bone cuts and improving surgical variables.<sup>5</sup> Newer robotic platforms provide clinicians the ability to compare objective intraoperative data with the collection of validated patient-reported outcome measures (PROMs). This comprehensive review investigates historical and commercially available systems, technically demanding skill, clinical outcomes, cost analysis, and limitations to better understand the value of RA-TKA.

## History

In 1985, the first surgical robot system was used in a clinical procedure for neurosurgical biopsies.<sup>6</sup> By the late 1980s, surgical robots demonstrated a clear advantage over computer navigation alone with improved three-dimensional (3D) accuracy and increased procedural precision with the most potential in neurosurgery, urology, and orthopaedic surgery.<sup>7</sup> The first orthopaedic robotic-assisted system was developed in 1986 and was used for noncemented total hip arthroplasty.<sup>8</sup> During the past two decades, robotic implementation in orthopaedic TJA procedures has steadily increased with an estimated global market for medical robotics to surpass \$20 billion by 2023.<sup>9</sup>

## Robotic Total Knee Arthroplasty Platforms Image-based Versus Imageless

Robotic systems typically require preoperative plain radiographs or CT scans to use in a mapping process to re-create a 3D virtual knee template for preoperative and intraoperative planning. Preoperative imaging allows consideration of the

patient's distinct anatomy, which serves as a model for accurate implant placement and intraoperative adjustments. However, additional increased cost and radiation exposure are potential disadvantages of image-based systems. Furthermore, preoperative CT exposure can have a radiation dose (100 mSv) markedly greater than the FDA's threshold of effective radiation dose (10 mSv) for increased malignancy risk.<sup>10</sup>

Although imageless platforms reduce surgical time and radiation exposure, they are solely reliant on the surgeon's accuracy during bony landmark registration. Patients with notable deformity or bone loss may have altered anatomic landmarks, which can pose a challenge during robotic registration.

## Closed Versus Open Platforms

Closed systems are only compatible with manufacturer-specific implant designs. Most available robotic systems in the United States are regarded as closed platforms. This may hamper widespread robotic adoption for surgeons who are accustomed to using certain implants that do not offer a robotic platform. Conversely, open platform systems accommodate several prosthesis designs from multiple different manufacturers for 3D templating and surgical planning. However, open platforms may lack detailed biomechanical kinematic data present in closed platforms that use trademarked implants.<sup>11</sup>

## Active, Semiactive, or Passive Robotic Systems

### Background

Every robotic design has varying levels of constraint and haptic feedback, which are classified as (1) *active* (2) *semiactive*, or (3) *passive* systems. *Active robotic TKA platforms* perform a designated task completely independent of the surgeon. After the surgeon calculates the optimal bony resection and final implant placement and alignment on the robotic computer software, an intraoperative robot executes the preoperative plan with a high level of precision and accuracy.<sup>10</sup> *Semiactive robotic TKA* systems provide the tactile feedback with procedural safeguards to ensure accuracy and safety against iatrogenic soft-tissue or neurovascular injury that may occur with active platforms.<sup>10</sup> Semiactive modalities use haptic feedback through auditory, tactile, or visual cues that notify deviations from the preoperatively defined boundaries.<sup>10</sup> Semiactive robots also self-regulate instrumentation that either slows down or completely stops when deviation outside the computer-generated volume or depth of a defined bone resection

occurs. Unlike active and semiactive designs, *passive robotic TKA systems* assist in surgical procedures under complete continuous and direct surgeon control. These systems create computer-assisted 3D templating from either preoperative CT scans or imageless intraoperative landmark registration.

## Active Total Knee Arthroplasty Robotic Systems

### Historical Systems

The first-generation RA-TKA systems that were used in Europe in the late 1980s were active robotic platforms. Although these robotic designs garnered initial interest with short-term success, the older generation active robots required an initial surgical procedure for fiducial marker placement before CT scan imaging.<sup>10</sup> The older platforms also added notable surgical time because of a lack of streamlined workflow and were associated with higher blood loss.<sup>12,13</sup> Although RA-TKA demonstrated greater limb alignment restoration accuracy compared with conventional TKA, early active robotic systems had high rates of short-term complications including soft-tissue wound healing complications, patellar tendon ligament rupture, patella dislocation, supracondylar fracture, and patellar fracture and common peroneal injury.<sup>14</sup> The first-generation RA-TKA systems soon fell out of favor after poor early clinical outcomes and high failure rates.<sup>12,13</sup> Historical RA-TKA systems are summarized in Table 1.

### Contemporary Systems

Currently, one active robotic platform is available in the United States for primary TKA. The active system is a newer generation open platform system from an older design that was primarily used in Europe for TJA. The newer generation system is fiducial free and uses a digitizer to collect data points and locate the patient's exact

position to autonomously mill joint surfaces for component placement.<sup>10</sup> Although the surgeon maintains control over the milling tool with a manual override button and is responsible for soft-tissue protection, the robot completes the bony preparation steps independently with consistent water cooling irrigation and removal of milling debris with minimal ability for adjustments, whereas the robot executes the preoperative plan.<sup>10,11</sup>

Although newer generation active RA-TKA systems improved limitations from predecessor historical platforms, limited clinical studies exist evaluating the efficacy and outcomes of contemporary active system designs.

## Semiactive Total Knee Arthroplasty Robotic Systems

### Historical Systems

Early generation tactile systems with haptic feedback demonstrated increased implant alignment and placement accuracy with more consistent ligament soft-tissue balance.<sup>15</sup> Older designs were also larger in size and difficult to maneuver intraoperatively and associated with markedly increased surgical times.<sup>10</sup> However, tactile systems and overall technological improvements addressed some of the mechanisms of failure of older active platforms, such as soft-tissue protection.<sup>16</sup> Radiological and clinical outcome improvement increased the popularity and paved the way for modern semiactive RA-TKA platforms.

### Contemporary Systems

Currently, three semiactive closed robotic platforms are available in the United States for primary TKA that use saw and burring for bony preparation. The first contemporary CT-based semiactive RA-TKA system integrates the robotic arm-guided sawblade with the preoperative plan. The intraoperative bony registration does not require rigid stabilization that was

**Table 1. Historical Robotic-Assisted Total Knee Arthroplasty Systems**

Name	CASPAR	Acrobot	PiGalileo	Puma 260	iBlock
Manufacturer	Orto Maquet/URS, Schwerin, Germany	Imperial College of London	Plus Orthopedics AG, Rotkreuz, Switzerland	RP Automation Inc, Pittsburgh, Pennsylvania	PRAXIM SA, La Tronche, France
Platform	Open	Closed	Closed	Open	Closed
Type	Active	Semiactive	Passive	Passive	Passive
Technique	Milling	Saw	Cutting guide	Cutting guide	Cutting guide
Image	CT	CT	CT	CT	Imageless

Acrobot = The active constraint robot, CASPAR = computer-assisted surgical planning and robotics

needed in older robotic designs and allows for dynamic femur and tibia assessment.<sup>13</sup> After bony registration, implant positions are virtually adjusted to obtain equal flexion and extension gaps and overall alignment. The robotic arm is used to perform bony cuts and has haptic feedback if the saw deviates beyond the predetermined cutting zones<sup>13</sup> (Figure 1). The haptic guide, however, does not routinely recognize aberrant soft-tissue interposition, so careful retractor placement remains critical. Comparison between two modern active and semiactive systems are summarized in Table 2.

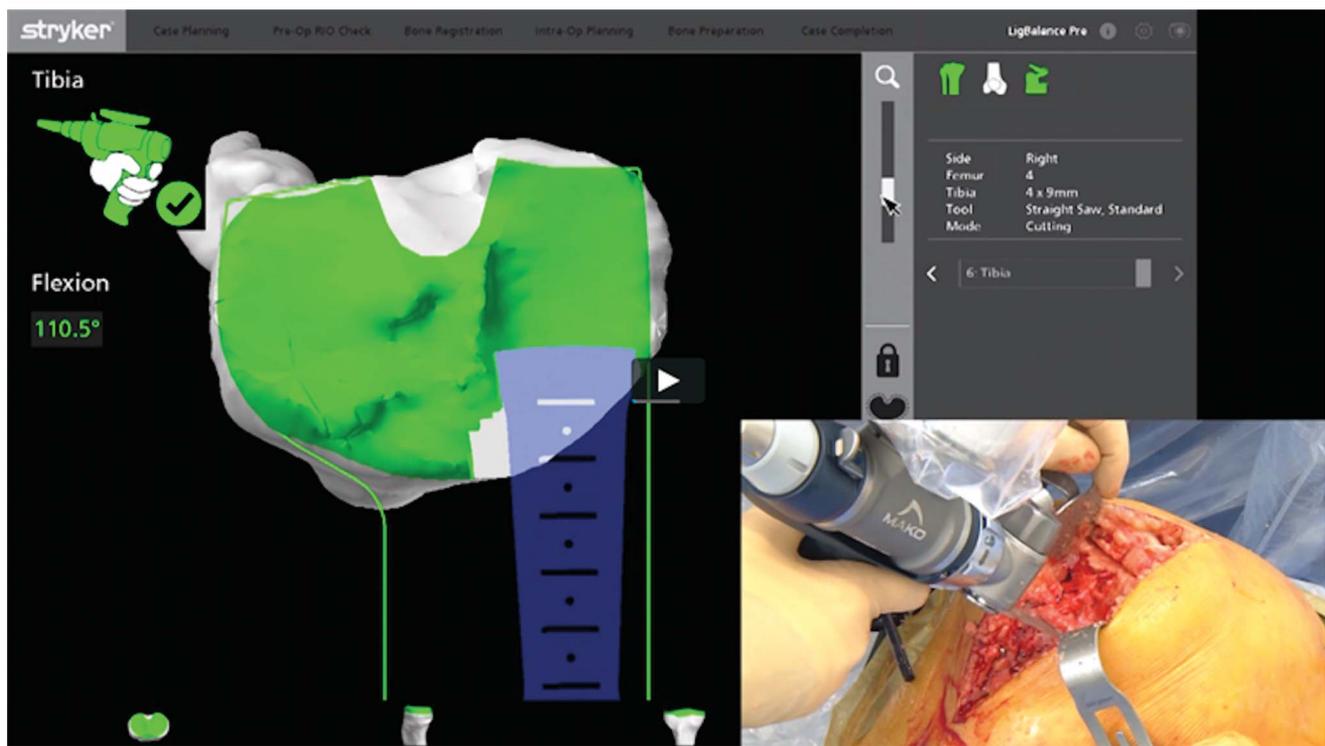
The second contemporary semiactive RA-TKA more recently received FDA clearance for TKA in 2017.<sup>10</sup> The imageless system uses a handheld end-cutting burr that allows the surgeon to perform predefined bone cuts using digital-based reference points.<sup>13</sup> Preset parameters limit excessive bone resection, whereas the robotic tool alters the burr speed and retracts the burr tip to prevent errors.<sup>10,13</sup> The imageless system also eliminates clinically relevant preoperative imaging costs and associated radiation exposure.

The third semiactive system is a closed platform robotic arm that aids in the placement of the cutting

block and dynamic ligament balancing that recently obtained FDA clearance for TKA in 2019.<sup>17</sup> Preoperative full length lower extremity two-dimensional radiographs are converted intraoperatively to 3D images has a reported accuracy within 0.4° for angle measurement.<sup>17,18</sup> After bony registration, the flexion and extension gaps are evaluated to determine the optimal depth of bony resection and planned implant positioning and alignment for equal medial and lateral, flexion, and extension gaps. The plan is executed with the robotic arm locking the cutting jig in the desired position for bone resection with a conventional saw.<sup>17,18</sup>

Most of the literature reporting RA-TKA surgical efficiency, clinical outcomes, and cost effectiveness involves the CT-based robotic arm design because it was one of the earlier contemporary systems to receive FDA clearance for primary TJA.<sup>10</sup> There are current ongoing prospective studies further investigating semiactive robotic burring system efficacy versus conventional TKA. Future clinical studies are warranted to evaluate implant longevity, complications, functional outcomes, and patient satisfaction after semiactive RA-TKA.

**Figure 1**



Photograph demonstrating a semiactive robotic system computer software demonstrating tibial resection with surrounding haptic boundaries (adjacent green lines) while protecting the posterior cruciate ligament posteriorly. (Courtesy of Stryker Orthopedics, Mahwah, NJ)

**Table 2.** Comparison Between Two Modern Semiactive Robotic Systems

Factors	Mako	ROSA
Manufacturer	Stryker, Mahwah, NJ	Zimmer Biomet, Warsaw, IN
FDA clearance	2015	2019
Applications	TKA, UKA, THA	TKA
Robotic arm attachment	Saw blade	Cutting guide
Preoperative imaging	CT scan	Plain radiographs or imageless
Registration points	92 points	17 points
Number of TKA systems available	Triathlon total knee system	NexGen LPS; Persona knee system; Vanguard knee system
Comparison	Haptic feedback limits surgeon sawing beyond the bone cut boundaries	No haptic feedback
	Flexion and extension gaps balanced through bone cuts	Cutting block secured on native bone for bony preparation using conventional oscillating saw
	Soft-tissue tension assessed at 0° extension and 90° flexion	Robotic plan able to be verified using conventional instrumentation
		Soft-tissue tension assessed and recorded automatically throughout range of motion

THA = total hip arthroplasty, TKA = total knee arthroplasty, UKA = unicompartmental knee arthroplasty

## Passive Total Knee Arthroplasty Robotic Systems

### Historical Systems

Both CT-based and imageless passive robotic systems have been used in primary TKA. Older generation passive RA-TKA platforms helped position cutting jigs, drill guides, and oscillating saws regarding the patient's bony geometry. The drill guides were hardened steel cylinders that determined the path of the drill in making holes for implant pegs.<sup>19</sup> Early passive systems often necessitated rigid femur and tibia fixation to the operating room table.<sup>19</sup>

Other older passive RA-TKA systems used imageless anatomic knee mapping and limb kinematic analysis to construct a virtual 3D model. The rigid probes with retro-reflective markers are localized in 3D space with optical infrared cameras. The imageless robotic instrument required rigid bony fixation to the medial aspect of the distal femur using cancellous bone screws.<sup>20</sup> However, the large bulk size of robotic guides with rigid fixation and the development of active and semiactive designs led to decreased passive RA-TKA platform utilization.

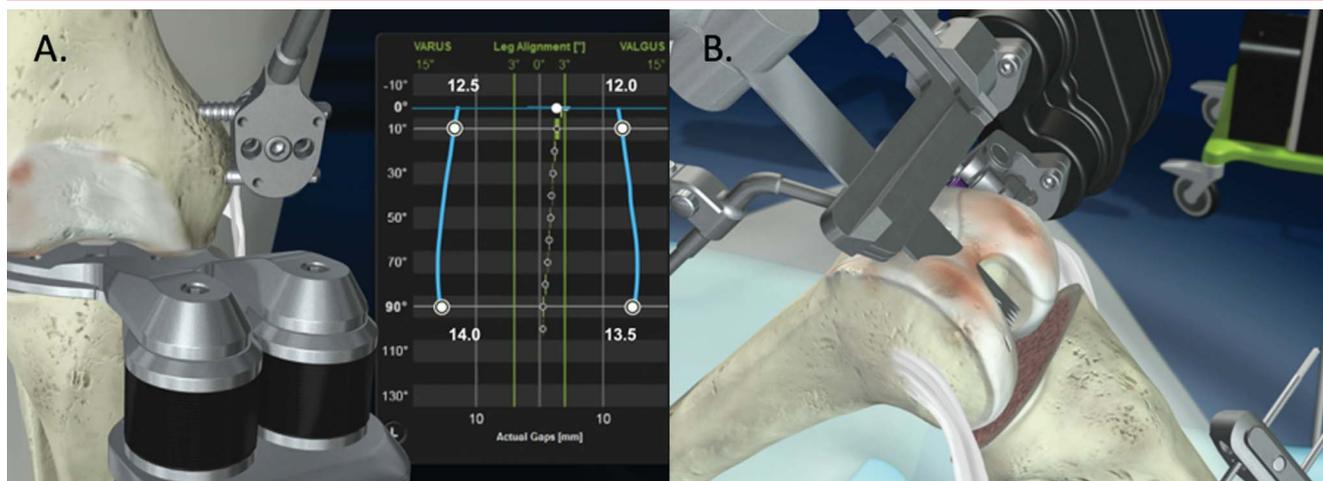
### Contemporary Systems

There is only one closed platform passive RA-TKA system, to our knowledge, is commercially available in the United States. After intraoperative registration and

integration with a preoperative CT scan, the miniature robotic cutting guide is clamped onto the bone using two motorized actuators with integrated force sensors.<sup>3</sup> The system uses a robotic soft-tissue balancer in conjunction with the cutting guide by providing soft-tissue tension measurement at various degrees of range of motion before any femoral cuts<sup>3</sup> (Figure 2). After femoral and tibial resections, the robot helps determine optimal polyethylene insert thickness that will provide the best overall balance. Clinical outcomes are yet to be determined because this newer passive RA-TKA was recently FDA approved in 2017. The main robotic-assisted systems currently used in the United States are summarized in Table 3.

### Technically Demanding Skill

When adopting a new surgical technique and implementing technology in TKA, understanding the technically demanding skill and its impact on surgical workflow is pivotal. RA-TKA has been shown to have a short technically demanding skill regarding surgical time<sup>21</sup> and short-term outcomes.<sup>22</sup> Kayani et al<sup>21</sup> prospectively recorded surgical times for 60 conventional TKA, followed by 60 RA-TKA performed by a surgeon who only had cadaveric RA-TKA experience and

**Figure 2**

**A.** Photograph demonstrating a robotic laminar spreader to measure soft-tissue tension throughout motion before making any femoral resections. **B.** A patient-mounted apparatus that robotically positions a single resection slot to perform all femoral resections according to the surgeon's plan. (Courtesy of Corin, Raynham, MA.)

found a notable decline in the surgical time after the seventh surgical case. The study also found no technically demanding skill regarding implant placement accuracy and limb alignment without additional complication rates. Similarly, Grau et al<sup>23</sup> reported a technically demanding skill of six cases before surgical times reached within one standard deviation of the average for the subsequent 132 RA-TKA cases. Although surgical times are increased in the learning phase of RA-TKA, surgical workflow seems to be comparable with traditional TKA after proficiency has been achieved.<sup>15</sup>

## Clinical Outcomes

### Soft-tissue Protection

RA-TKA's ability to safeguard periarticular soft-tissue integrity with minimal releases and decreased surrounding tissue injury may mitigate local inflammatory response resulting in decreased postoperative pain and swelling.<sup>15,24</sup> In a retrospective study, Siebert et al<sup>12</sup> compared 70 RA-TKA patients versus 50 conventional TKA patients and found decreased postoperative soft-tissue swelling in the robotic cohort. In a prospective cohort study comparing 30 conventional TKA with 30 RA-TKA, Kayani et al<sup>25</sup> demonstrated RA-TKA patients had reduced medial soft-tissue injury in passively correctable ( $P < 0.05$ ) and fixed varus deformities ( $P < 0.05$ ), more accurate femoral and tibia bone cuts ( $P < 0.05$ ), and less macroscopic soft tissue injury compared with conventional TKA. This decreased swelling may be an

association of greater initial postoperative range of motion compared with conventional TKA with reports of 4.5-fold decrease in manipulation under anesthesia rates after RA-TKA up to the 2-year follow-up<sup>26</sup> (Table 4).

### Patient-reported Outcome Measures

Regardless of the improved precision of RA-TKA, the value of technology-assisted TKA is reliant on the determination of whether the improved accuracy influences functional outcomes and implant survivorship. Short-term follow-up studies have demonstrated RA-TKA to have greater functional outcome and pain PROM scores.<sup>27,28</sup> A prospective multicenter investigation found RA-TKA to have markedly larger improvements in walking and standing and satisfaction and expectation scores ( $P < 0.05$  for all) compared with manual TKA patients at 6 weeks postoperatively. These findings were extended out to 3 months with RA-TKA having larger improvements in walking and standing, standard and advanced activities, functional activity total score, pain with walking, total symptoms score, satisfaction, and expectation scores ( $P < 0.05$  for all) compared with conventional TKA.<sup>29</sup>

In a randomized control trial, Blyth et al<sup>30</sup> found patients with robotic-assisted surgery demonstrating improved early pain scores and function scores, but no differences observed at 1-year postoperatively. Similarly, Hansen et al<sup>31</sup> found that although both robotic and manual arthroplasty procedures in two matched cohorts resulted in reproducible and excellent outcomes with low complication rates, no radiographic or clinical

**Table 3.** Main Robotic-Assisted Total Knee Arthroplasty Systems in the United States

Name	TSolution-One	ROSA	Mako	Navio	Orthotaxy	CORI	OMNibotic
Manufacturer	THINK Surgical, Fremont, CA	Zimmer Biomet, Warsaw, IN	Stryker, Mahwah, NJ	Smith & Nephew, Memphis, TN	DePuy Synthes, Warsaw, IN	Smith & Nephew, Memphis, TN	Corin, Tampa, FL
Platform	Open	Closed	Closed	Closed	Closed	Closed	Closed
Type	Active	Semiactive	Semiactive	Semiactive	Semiactive	Semiactive	Passive
FDA clearance	2019	2019	2015	2017	Pending	Pending	2017
Technique	Milling	Cutting guide	Saw or burr	Burr	Saw	Burr	Cutting guide
Image	CT	XR or imageless	CT	Imageless	CT	Imageless	CT
Status	Available	Limited release	Available	Available	Pending	Pending	Available

difference existed in outcomes between the cohorts that could justify the routine utilization of costly robotic systems. Conversely, in a prospective, multicenter study, Kleeblad et al<sup>32</sup> reported high survival (97%) and satisfaction rates (91%) of 432 robotic procedures at midterm 5.7-year follow-up. However, these reports evaluated RA-unicompartmental knee arthroplasty, which may limit the extrapolation of the results after TKA.

A systematic review and meta-analysis of 323 RA-TKAs and 251 traditional TKAs reported greater improved Knee Society score functional outcomes and Western Ontario and McMaster Universities Osteoarthritis Index scores in the RA-TKA cohort group at the 6-month follow-up. Similarly, Kayani et al<sup>28</sup> found RA-TKA patients to have less pain, decreased analgesic requirements, and reduced physical therapy duration compared with conventional TKA. In another multicenter study, Malkani et al<sup>33</sup> reported RA-TKA patients to have improved functional, quality of life, and global health assessment scores that were seen at a minimum 2-year follow-up. However, improved RA-TKA implant positioning, alignment, and short-term PROMs have not implicated any conclusive difference in midterm to long-term functional outcomes compared with conventional TKA.<sup>15</sup> In a recent large meta-analysis of 2,234 RA-TKA and 4,300 conventional TKA, Onggo et al<sup>34</sup> found superior precision of prosthesis implantation in RA-TKA compared with conventional TKA, but no difference in clinical outcomes or complication profiles of both cohorts. Few studies have similarly reported no difference in Hospital for Special Surgery, Western Ontario and McMaster Universities Osteoarthritis Index, Oxford Knee Scores, Knee Society score,

or Short-Form 12 scores at a minimum 10-year follow-up<sup>35,36</sup> (Table 5).

### Implant Survivorship

Although conventional TKA has shown excellent long-term survivorship,<sup>37</sup> RA-TKA has increased in popularity in an effort to further improve implant longevity and functional outcomes while decreasing revision rates and cost continue to be critical in providing value-based care. Improved positioning may translate to greater survivorship because varus tibial alignment greater than 3° and femoral malalignment has been associated with early failure.<sup>38</sup> Although RA-TKA has improved limb alignment restoration,<sup>38</sup> inconclusive literature exists on the effect of long-term implant survivorship, revision rates, and complications. However, a recent prospective, randomized control trial found no differences between RA-TKA and conventional TKA for functional outcome scores, aseptic loosening, overall survivorship, and complications at a minimum 10-year follow-up.<sup>39</sup> Current studies reporting radiologic and clinical outcomes after RA-TKA are summarized in Table 6.

### Computer-navigation and Patient Specific Instrumentation

CAN, patient-specific instrumentation (PSI), and robotic surgery have evolved in the attempt to customize TKA for each individual patient. Although these techniques reduce the number of outliers and position implants more reliably, each modality has demonstrated varying clinical results and cost effectiveness.<sup>40</sup> Despite notable advances in CAN and PSI, notable midterm and long-term clinical function outcomes and survivorship have been shown to be similar to conventional TKA despite

**Table 4. Soft-tissue Protection Outcomes After Contemporary Robotic-Assisted TKA**

Study	Year	System	Robotic Cases (No.)	Conventional Cases (No.)	Follow-up (mo)	Conclusions	Level of Evidence
Kayani et al <sup>25</sup>	2018	Mako	30	30	—	Patients undergoing RA-TKA had reduced medial soft-tissue injury in both passively correctable ( $P < 0.05$ ) and fixed varus deformities ( $P < 0.05$ ), more accurate femoral ( $P < 0.05$ ) and tibial ( $P < 0.05$ ) bone resection cuts, and improved macroscopic soft-tissue injury scores compared with conventional TKA ( $P < 0.05$ ).	3
Malkani et al <sup>26</sup>	2019	Mako	188	188	24	Patients undergoing RA-TKA experienced a significant, 4.5-fold decrease in rates of MUA ( $P = 0.032$ ).	3
Khlopas et al <sup>52</sup>	2017	Mako	6	6	—	During bone resections, the tibia in RA-TKA procedures did not require subluxation, which may reduce ligament stretching or decrease complication rates. Although RA-TKA uses a stereotactic boundary to constrain the sawblade, which is generated based on the implant size, shape, and plan, it does not routinely recognize interposed soft tissue; therefore, meticulous retractor placement is critical.	5
Hampp et al <sup>24</sup>	2019	Mako	12	12	—	Significantly less damage occurred to the PCLs in the RA-TKA versus the manual TKA specimens ( $P < 0.001$ ). RA-TKA specimens had nonsignificantly less damage to the deep medial collateral ligaments ( $P = 0.149$ ), iliotibial bands ( $P = 0.580$ ), popliteus ( $P = 0.248$ ), and patellar ligaments ( $P = 0.317$ ).	5

PCL = posterior cruciate ligament, RA-TKA = robotic-assisted TKA, TKA = total knee arthroplasty

improved radiographic alignment and fewer outliers achieved with navigation and PSI assistance.<sup>41-43</sup>

Although no literature exists directly comparing RA-TKA versus PSI, contemporary RA-TKA has reported improved accurate implant position, limb alignment, and shorter hospital lengths of stay compared with conventional and CAN-TKA.<sup>20,38</sup> However, it is important to understand that most

literature concerning technology-assisted TKA are performed at academic centers with fellowship-trained arthroplasty surgeons. Equivocal results regarding technology-assistance compared with conventional TKA may be a byproduct of experience and surgical familiarity.<sup>31,44</sup> The benefit of these technologies for community surgeons who may not be as facile in arthroplasty procedures is yet to be determined.<sup>43</sup>

**Table 5. Patient-reported Outcome Measure Outcomes of Contemporary robotic-assisted TKA Systems**

Study	Year	System	Robotic Cases (No.)	Conventional Cases (No.)	Follow-up (mo)	Conclusions	Level of Evidence
Song et al. <sup>53</sup>	2013	ROBODOC	50	50	41	No differences in postoperative ROM, WOMAC scores, and HSS knee score.	1
Liow et al. <sup>5</sup>	2014	ROBODOC	31	29	6	No overall difference in clinical outcome measures, except in SF-36 vitality scores, where the robot-assisted group reported higher vitality scores at the 6-mo follow-up	1
Liow et al. <sup>11</sup>	2017	ROBODOC	31	29	24	Despite having a higher rate of complications, RA-TKA displayed a trend toward higher scores in SF-36 QoL measures, with significant differences in SF-36 vitality ( $P = 0.03$ ) and role emotional scores ( $P = 0.02$ ). No significant differences in KSS, OKS or satisfaction/expectation rates at the 2-yr follow-up	1
Kayani et al. <sup>25</sup>	2018	Mako	40	40	1	Robotic arm-assisted TKA was associated with reduced postoperative pain ( $P < 0.001$ ), decreased analgesic requirements ( $P < 0.001$ ), 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.	2
Khlopas et al. <sup>29</sup>	2019	Mako	150	102	3	RA-TKA patients had equal or greater improvements in 9 of 10 of the Knee Society scoring system components assessed at 3 mo postoperatively.	2
Onggo et al. <sup>34</sup>	2020	ROBODOC, Mako, Navio	2,234	4,300	—	The authors found superior precision in prosthesis implantation in RA-TKA compared with conventional TKA, but the clinical outcomes and complication profiles of both groups were comparable.	2

(continued)

**Table 5.** (continued)

Study	Year	System	Robotic Cases (No.)	Conventional Cases (No.)	Follow-up (mo)	Conclusions	Level of Evidence
Marchand et al <sup>54</sup>	2017	Mako	20	20	6	The mean physical function score for the manual and robotic cohorts were $9 \pm 5$ and $4 \pm 5$ , $P = 0.055$ , respectively. The mean total patient satisfaction score for the manual and robotic cohorts were 14 points and 7 points, $P < 0.05$ , respectively.	3
Marchand et al <sup>55</sup>	2019	Mako	53	53	12	The RA-TKA cohort had significantly improved mean total ( $6 \pm 6$ versus $9 \pm 8$ points, $P = 0.03$ ) and physical function scores ( $4 \pm 4$ versus $6 \pm 5$ points, $P = 0.02$ ) when compared with the manual cohort. The mean pain score for the RA-TKA cohort ( $2 \pm 3$ points [range, 0-14 points]) was also lower than that for the manual cohort ( $3 \pm 4$ points [range, 0-11 points]) ( $P = 0.06$ ) at the 1-yr follow-up. RA-TKA was found to have the strongest association with improved scores when compared with age, sex, and BMI.	3
Khlopas et al <sup>29</sup>	2019	Mako	150	102	3	RA-TKA patients were also found to have larger improvements in walking and standing, standard activities, advanced activities, functional activities total score, pain with walking, total symptoms score, satisfaction score, and expectations score when compared with manual TKA patients at the 3-mo follow-up	3

BMI = body mass index, HSS = Hospital for Special Surgery, KSS = Knee Society score, MUA = manipulation under anesthesia, OKS = Oxford Knee Scores, QoL = quality of life, RA-TKA = robotic-assisted TKA, ROM = range of motion, SF-36 = Short-Form 36, TKA = total knee arthroplasty, WOMAC = Western Ontario and McMaster Universities Osteoarthritis Index

### Cost Analysis

In today’s value-based cost-conscious healthcare environment, the prospect of robotics in TJA depends markedly on the consideration of the quality of care relative to cost.

Robotic technology presents with substantial upfront and maintenance expenditure (range from \$400,000 to \$1.5 million)<sup>15</sup> in addition to preoperative plain radiograph or advanced imaging, disposable instrumentation cost, increased operating times during the learning phase, and

**Table 6.** Radiologic and Clinical Outcomes of Contemporary Robotic-Assisted TKA Systems

Study	Year	System	Robotic Cases (No.)	Conventional Cases (No.)	Follow-up (mo)	Conclusions	Level of Evidence
Kim et al <sup>39</sup>	2020	ROBODOC	975	990	120	No differences between RA-TKA and conventional TKA for functional outcome scores, aseptic loosening, overall survivorship, and complications at minimum 10-yr follow-up.	1
Ren et al <sup>27</sup>	2019	ROBODOC, CASPAR	315	262	16-120	Compared with conventional surgery, active robotic TKA showed better outcomes in precise mechanical alignment ( $P < 0.05$ ) and implant position, with lower outliers ( $P < 0.05$ ).	2
Clark and Schmidt <sup>20</sup>	2013	OMNIBotic	52	29	1	The average absolute intraoperative malalignment was 0.5° less in the RA-TKA procedures compared with the computer navigation procedures.	3
Yang et al <sup>35</sup>	2017	ROBODOC	71	42	120	RA-TKA had significantly fewer postoperative leg alignment outliers (femoral coronal inclination, tibial coronal inclination, femoral sagittal inclination, tibial sagittal inclination, and mechanical axis) and fewer radiolucent lines compared with conventional TKA.	3
Cho et al <sup>36</sup>	2019	ROBODOC	155	196	132	The conventional TKA group showed a significantly higher number of outliers compared with RA-TKA group ( $P < 0.05$ ). The cumulative survival rate was similar between groups (98.8% in RA-TKA and 98.5% in conventional TKA [ $P = 0.563$ ]).	3

(continued)

**Table 6.** (continued)

Study	Year	System	Robotic Cases (No.)	Conventional Cases (No.)	Follow-up (mo)	Conclusions	Level of Evidence
Marchand et al. <sup>55</sup>	2019	Mako	335	—	1	For 98% of prostheses, RA-TKA software predicted within 1 implant size the actual tibial or femoral implant size used. The robotic software and use of a preoperative CT substantially helped with intraoperative planning and accurate prediction of implant sizes.	4

RA-TKA = robotic-assisted TKA, TKA = total knee arthroplasty

platform updates.<sup>15</sup> Although disposable instruments have greater manufacturing expense, recent studies have shown the potential of reducing operating room times over conventional reusable sets with improvements reported with operating room turnover time, efficiency, sterile processing, and logistics of loaner instrumentation.<sup>45</sup> However, indirect costs for performing RA-TKA have not been reported in the literature, which may substantially alter the overall cost of robotic surgery. Indirect costs include the cost of travel and parking to the imaging facility, opportunity cost, and economic impact for the time patient has to spend off from work while obtaining imaging, cost of time spent by technologist to complete specific imaging protocol, cost of radiologist reviewing imaging and editing protocol as needed, cost of time spent by engineers sequencing preoperative imaging to allow virtual templating, cost of time spent by surgeons reviewing and validating preoperative plan, cost of transportation and handling of disposable equipment and instruments, cost of reusable sets, difference in hospital stay with RA-TKA versus conventional surgery, difference in the number of radiographs with RA-TKA versus conventional surgery, and differences in total time spent at home before returning to work full-time.

Although the use of RA-TKA has increased over the past decade, some insurance companies do not approve RA-TKA or preoperative CT imaging as a medical necessity,<sup>46</sup> potentially leaving uncovered expenses to the patient's financial responsibility or requiring additional justification as medical necessity or different treatment planning codes for insurance authorization.

Furthermore, widespread incorporation of new technologies should be coupled with the anticipated short-term and long-term benefits, outcomes, and

reduced complications beyond the robotic technology cost. However, the initial capital expense may be equi-poised with RA-TKA's cost savings from reduced analgesic consumption, decreased hospital lengths of stay, readmission rates, and greater home self-care discharges.<sup>15</sup> In a cost comparative study between RA-TKA and a propensity-matched conventional TKA cohort, Mont et al<sup>47</sup> found RA-TKA to be associated with lower 30 day (\$17,768 versus \$19,899;  $P < 0.0001$ ), 60 day (\$18,174 versus \$20,492;  $P < 0.0001$ ), and 90-day (\$18,568 versus \$20,960;  $P < 0.0001$ ) postoperative total costs and healthcare utilization. At 30 days, 47% fewer RA-TKA patients used skilled nursing facility services (13.5% versus 25.4%;  $P < 0.0001$ ) and 31.3% fewer RA-TKA patients used emergency department services. RA-TKA was also associated with lower 90-day readmissions (5.20 versus 7.75%;  $P = 0.0423$ ).

Similarly, Cool et al<sup>48</sup> compared 519 RA-TKA with a propensity-matched 2,595 conventional TKA patients and determined 90-day episode-of-care costs between cohorts. Overall, 90-day episode-of-costs were \$2,391 less costly for RA-TKA ( $P < 0.0001$ ), driven by fewer readmission (5.2% versus 7.8%) and greater home discharges (56.7% versus 46.7%).<sup>48</sup> Overall index facility costs to insurance companies for RA-TKA were found to be markedly less than those for conventional TKA (\$12,384 versus \$13,024;  $P = 0.0001$ ). The authors noted that the index facility cost varied between hospitals because diagnosis-related-group payments varies by hospital based on factors including geographic wage index differences.<sup>48</sup> However, these CMS administrative database studies are limited in the ability to determine claims costs versus true hospital facility

costs and may not be representative of the overall cohort.

Although RA-TKA has shown short-term success, longer term success with improved survivorship and patient satisfaction with decreased rates of revision arthroplasty will continue to determine the value of robotic technology in TKA.

## Ergonomic Health

Operating room physical burdens are known causes of overuse musculoskeletal injuries among arthroplasty surgeons from ergonomically compromised postural positions.<sup>49</sup> In a cadaver study, Scholl et al<sup>49</sup> demonstrated greater shoulder and low back muscle stimulation during bone preparation and implant trialing in surgeons performing conventional TKA compared with RA-TKA. Other studies have suggested that RA-TKA further reducing physical stress on the cervical and thoracic spine by providing eye-level robotic software display with potential long-term physical health benefits.<sup>50</sup> Further prospective in-vivo studies are needed to determine surgeon health longevity compared with conventional TKA that may further expand robotic technology's value.

## Limitations

Robotic technology has limitations worth noting. RA-TKA requires additional incision or longer incisions for femoral and tibial registration pins accommodation.<sup>15</sup> Tracking percutaneous pins create potential stress risers and risk of periprosthetic fractures, especially if placed in diaphyseal bone. Accidental pin placement beyond the second cortex increases theoretical risk of neurovascular injury. Despite improvement of workflow and efficiency, intrinsic time delays are unavoidable both preoperatively for implant templating and intraoperative plan adjustment. This is clinically relevant because every 20-minute increase in surgical duration is associated with nearly a 25% increased risk of subsequent periprosthetic joint infection.<sup>51</sup> However, recent studies have shown a short technically demanding skill with surgical time durations approaching conventional TKA surgical duration in less than 10 cases.<sup>21,23</sup> Finally, although newer active and semiactive robotic systems have advanced to better protect surrounding soft tissues, it is still imperative for surgeons to appropriately place retractors to prevent any iatrogenic ligamentous or neurovascular damage.

## Summary

In today's healthcare shift toward an increased emphasis on quality of care, while curtailing costs, the new era in care delivery seeks to optimize procedural value.<sup>1</sup> RA-TKA has shown improved predictability and precision in planned alignment restoration with improvement in early functional outcomes and 30-day, 60-day, and 90-day global episode-of-care cost savings compared with conventional TKA.<sup>52-55</sup> However, multiple indirect costs exist that need to be considered when determining the overall cost effectiveness of RA-TKA. With robotic technology progressively evolving, longer term studies assessing implant survivorship and complications will continue to determine whether the initial capital investment is offset with improved outcomes. Because predictability in health care carries a premium similar to any other economical branch, RA-TKA's ability to decrease procedural variability adds value to arthroplasty procedures because patients and healthcare providers both seek to obtain predictable and dependable outcomes.<sup>56</sup> Furthermore, the success and return on investment of robotic technology may transition to be measured by its ability to minimize the standard deviation of the targeted outcome as opposed to altering the outcome itself.

## References

Levels of evidence are described in the table of contents. In this article, references 5, 30, 38, 41, and 45 are level I studies. References 15, 17, 25, 28, and 29 are level II studies. References 2, 14, 20, 26, 27, 31, 32, 34, 35, 37, 39, 42, 44, 47, 48, 51, 52, 53, 54, and 55 are level III studies. References 8, 11, 12, 15, 22, 23, 33, and 36 are level IV studies. References 18, 24, and 49 are level V studies.

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