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Robots on the Stage: A Snapshot of the American Robotic Total Knee Arthroplasty Market

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Abstract

- Computer-assisted robots aid orthopaedic surgeons in implant positioning and bony resection. Surgeons selecting a robot for their practice are faced with numerous options. This study aims to make the choice less daunting by reviewing the most commonly used Food and Drug Administration-approved robotic total knee arthroplasty platforms in the American arthroplasty market.
- Modern total knee arthroplasty (TKA) robots use computer guidance to create a virtual knee model that serves as the surgeon's canvas for resection planning.
- Most available robotic TKA (rTKA) systems are closed semiactive systems that restrict implant use to those of the manufacturer.
- Each system has distinct imaging requirements, safety features, resection methods, and operating room footprints that will affect a surgeon's technique and practice.
- Robots carry different purchase, maintenance, and equipment costs that will influence patient access across different socioeconomic groups.
- Some studies show improved early patient-reported outcomes with rTKA, but long-term studies have yet to show clinical superiority over manual TKA.

Introduction

Robot-assisted surgery is used in many medical procedures, and knee arthroplasty is no exception. Robodoc (THINK Surgical) was the first robotic system used in orthopaedic surgery for total hip arthroplasty[1-3]. Advances in computer science have since led to improvements in navigation and robotic arm control. Popularity and use of robotic total knee arthroplasty (rTKA) systems have surged in recent years, comprising 13% of all TKAs according to the American Joint Replacement Registry 2023 report, a 3-fold increase from 2018[4,5].

In the modern arthroplasty context and for the purpose of this article, rTKA refers to surgery performed with a computer-guided resection tool, with or without an attached mechanical arm, with haptic or motion sensing feedback. Robotic systems are successors to previous "computer navigation" systems (sometimes referred to as just "navigation") that gave feedback to the surgeon without guiding implant positioning or resection[6]. Systems with computer navigation only or those lacking resection control through sensor feedback are outside the scope of this article. Modern arthroplasty robots create a virtual model of the joint that enables surgical planning[6-8]. They also help precisely execute the surgeon's plan using controlled resection tools[8-13].

Classifying Computer-Assisted Robots in Arthroplasty

Computer-assisted systems are broadly classified as passive, active, or semiactive (also known as haptic)[7,14]. Passive systems do not have an independent moving element. The computer only provides information regarding cut angles and implant position, but resection is manual. In active systems, a computer-controlled robot (usually an arm with multiple joints and a resection tool) autonomously performs resection based on entered parameters[7,14]. Semiactive systems combine elements of both passive and active: The computer helps guide planning, and a robotic resection tool is controlled by the surgeon. However, the computer also provides sensory feedback to help increase accuracy. Whether these systems translate to better safety and reliability is being studied[11,15,16].

Robotic systems are also subdivided into open vs. closed platforms. Open platform systems are compatible with a wide array of implants regardless of manufacturer. Closed platform systems are only compatible with the manufacturing vendor's implants[8]. This means adopting a closed robotic system also requires switching to that manufacturer's implants. There are currently multiple companies that offer Food & Drug Administration (FDA)-approved closed systems: robotic surgical assistant (ROSA) (Zimmer-Biomet), core of real intelligence (CORI) (Smith & Nephew), Velys (Depuy-Synthes), and

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Mako (Stryker). OMNIbotics (Corin) is also FDA approved in the United States for TKA[17].

Notably, the TMINI and TSolution-One (THINK Surgical) are the only available open platform systems. The TMINI features a motorized optically guided drill for traditional cutting block pins. TSolution-One, the successor to ROBODOC, is a computed tomography (CT)-based active robot with an autonomous milling tool. According to several authors, the TMINI and OMNIbotics are better classified as motorized computer navigation systems rather than robotic tools with haptic feedback[17]. Thus, these 2 systems are beyond the scope of this study.

Performing TKA With Computer Guidance

The process of performing robotic TKA can seem confusing at first, as it has several additional steps. It can be performed with image-based or imageless systems. To ensure familiarity with their devices, manufacturers require surgeons take rTKA certification courses before use.

Most computers in robotic arthroplasty receive information about the outside world by way of optical arrays. These arrays each contain reflective disks or spheres arranged in unique configurations that can be distinguished by the computer via a camera. A probe and resection tools are also attached to optical arrays. LEDs and reflective optical encoders (electromechanical devices that convert angular or linear displacement into electrical signals) are built into the camera and various moving parts, which convey information to the computer. Tibia and femur arrays are affixed to the patient via bone pins[18]. The mathematics and engineering underlying optical tracking and modeling are beyond the scope of this article. Simply, the computer obtains the position of the instruments, tibia, ankle, femur, hip center of rotation, and resection tools by recognizing the position and orientation of each array. Joint surface topography is also manually captured with the probe. The computer uses these aggregate data to reconstruct a virtual representation of the patient's tibia and femur[19]. Imageless systems use only intraoperative data. Image-based systems augment this process with radiograph, magnetic resonance imaging (MRI), or CT scan, although this adds cost, time, and radiation[20]. In such systems, the computer superimposes in vivo surface points onto a 3D model generated from the preoperative image. This orients and positions the virtual model correctly in space. Imageless robotic systems require registering far more surface points to generate a topographic joint map from scratch, at the benefit of minimizing cost and radiation. Coronal plane imbalance is captured in the model by moving the knee through full range of motion and applying varus/valgus stress. This incorporates ligament laxities into the flexion/extension gaps. Bony resection is then simulated on this virtual model. The proprietary computer of each vendor's system is preloaded with their implants' exact polyethylene, tibial, and femoral component dimensions. The computer can simulate the resultant coronal plane gaps for each resection plane size of the implant. The plan is finally fine-tuned, and resection is performed[21-23]. Soft-tissue releases can still be performed at the surgeon's discretion. The surgeon can also verify coronal balance by restressing with trial implants in place.

One exception to the optical guidance strategy is the TSolution-One, which uses 2 stabilizing arms, a registration arm with a probe and a resection arm with a milling tool all directly linked to the computer[21,24]. Since the knee is immobile in this workflow and components are directly connected, there is no need for optical tracking.

Errors in Computer Guidance

Handheld saw blades can change angle or deflect when running through sclerotic bone, introducing variability into the resection plane. Manual cutting blocks can also shift due to retraction or pin motion. Moreover, cutting block positioning relies on bony landmarks, an imprecise method[22]. Resection depth and angle errors are much smaller in rTKA, though not eliminated[23]. Several studies show lower cut variability in rTKA compared with manual TKA (mTKA)[25-27], thanks, in part, to built-in haptic controls and safety measures. Despite safeguards within each system, undetectable errors such as inaccurate topographic mapping, pin-site loosening during surgery, or pin motion can still create discrepancies between the virtual model and real patient anatomy[25,28]. Many vendors require presence of product specialists to help troubleshoot intraoperative errors. Regardless, surgeons must be prepared to revert to mTKA in the event of major malfunctions.

Robotic TKA Compared with Manual TKA

Patient Satisfaction

Patient satisfaction, alongside complication rates, is a primary determinant of rTKA value. An estimated 19% of TKA patients are dissatisfied with their outcome[26]. Surveys suggest this is multifactorial, with persistent postoperative knee pain and continued difficulty with activities of daily living being most quoted[26]. Researchers hope the added precision and accuracy of robotics will translate to better patient outcomes and satisfaction[27,29,49].

Importantly, patients often have higher levels of expectation from rTKAs compared with mTKAs due to proinnovation bias, which affects reporting[31]. Prospective blinded studies would eliminate these biases but present ethical and logistical concerns. A multicenter prospective study on rTKA reported that 9 of the 10 measures assessed by the Knee Society Scoring (KSS) System improved at 3 months[32]. In a study from the Function and Outcomes Research for Comparative Effectiveness in total joint replacement registry, patients assessed vvia the New Knee Society Score 2 years after rTKA reported greater satisfaction with their surgery, improved scores of pain, higher levels of recreation, and improved quality of life compared with mTKA[33]. However, this comparison does not control for significant variability in techniques, perioperative practices, and patient populations. Another prospective study found higher patient satisfaction on a Likert scale and KSS survey at 1 year with rTKA[34]. When satisfaction scores were reviewed from multiple comparative studies, the authors found variable results at the final follow-up ranging from 3 months to 2 years[12]. This is a difficult area of study with mostly low-level evidence in publication. The ongoing Robotic Arthroplasty Clinical and Cost-Effectiveness Randomized Controlled

Trial-knee in the United Kingdom aims to compare 1-year Forgotten Joint Score (FJS) between rTKA and mTKA and may present high-level evidence[35].

Clinical Outcomes and Survivorship

A recent retrospective multicenter study of 861 rTKAs demonstrated reproducible increases in Forgotten Joint Score (FJS) and Knee Injury and Osteoarthritis Outcomes Score for Joint Replacement across institutions[36]. These improvements are comparable with those of mTKA. When comparing rTKAs with mTKA at 2 years, one study reported greater pain reduction and function on the Western Ontario and McMaster Universities Arthritis Index (WOMAC) in cementless rTKAs than mTKAs[37]. Randomized controlled studies are scarce in this area, but one such study with 10-year minimum follow-up found no difference in University of California-Los Angeles activity, WOMAC scores, or Knee society scores in a South Korean population[18]. A meta-analysis of clinical and radiological outcomes in rTKA found a mean clinical follow-up time of 33.8 months for all 20 studies, with >5 years data available in only 5 studies[12]. Four of these studies were from South Korea using the ROBODOC, which is no longer available in the United States. The authors' combined analysis of studies with over 1-year follow-up showed higher hospital for special surgery and WOMAC scores with rTKA but no differences in range of motion or KSS[12]. Only one study had 11 years of prospective randomized data, which showed no difference in implant survivorship[15].

TKA revision rates, although low, are projected to increase in the future[38]. Advocates of rTKA cite reduced revision rates as a potential benefit. Kim et al. followed 71 robotic-assisted TKAs for 15 years and found an annual all-cause revision probability of 0.28% for rTKA, not statistically different from 0.49% in mTKA[15]. They also reported no difference in aseptic loosening at 10 years. Another study compared rates of progressive radiolucency in 80 rTKAs vs. 80 mTKAs and found no difference[37]. Recently, an analysis of rTKA in 9,220 Medicare beneficiaries (older than 65 years) from the American Joint Replacement Registry was performed[39]. After controlling for confounders such as surgeon, location, and comorbidities, the authors found no difference in odds of revision at 2 years. Unlike most studies, they saw an increased odds of instability (OR 1.6, 95% CI 1.0-2.4, $p = 0.04$) and pain (OR 2.1, $p < 0.001$) at 2 years in the rTKA cohort. This study is limited by small sample size for a registry study and only considers the Medicare age group, but the results contrast to existing studies.

Accuracy of Cuts

In multiple studies, implant alignment seems to be more precise and reproducible with haptic controlled robotic resection compared with conventional cutting blocks[11,12]. A meta-analysis of 1 robot also showed more consistent cut angles for robotic unicompartmental knee arthroplasty (UKA), although this did not translate to improved short-term patient outcomes[8]. The same findings were observed in multiple studies comparing cut angles in TKA[10,13,40]. A prospective randomized study from Song et al. saw fewer mechanical axis outliers (>±3°) in the robotic surgery group (0 vs. 12, $p < 0.001$)[10]. Another randomized study found that TKA angles with robotic guidance had far less variability when striving for ±3° of neutral mechanical alignment ($p < 0.01$)[11]. While neither study found specific alignment values translated to better patient-reported outcomes, they demonstrate that rTKA allows more consistent cuts. Xu et al. also showed rTKA resulted in far fewer lateral tibial component angle outliers, 3.0% vs. 29.4% in mTKA[40]. The meta-analysis by Agarwal et al. also found that rTKA had significantly fewer radiographic outliers in their combined analysis of 8 studies, despite 2 showing no difference[12].

Soft-Tissue Balancing and Alignment

Another crucial component of performing TKA is ligamentous balancing. Instability due to coronal plane imbalance is one of the leading reasons for revision TKA[41]. Numerous studies have shown that ligamentous imbalance can cause instability, implant loosening, and joint stiffness[38,41]. With traditional mechanical resection, soft-tissue releases are often required to compensate for coronal imbalances. rTKA aims to minimize the need for releases by accounting for preresection balance in the planning stage. Surgeons can plan resection angles that compensate for laxity/tightness and reassess balance between releases. Standardized digital tensioners are currently under development to reduce variability in laxity measurement.

Limb alignment and joint line obliquity changes also have a profound influence on knee kinematics and patient satisfaction. Computer-assisted robots allow resection planning with varying alignment philosophies (mechanical, kinematic, functional, etc), with or without restrictions[42]. The ability to quantify the effects of resections/releases may eliminate some variability when comparing TKAs performed with different alignment philosophies. This may benefit surgeons looking to study outcomes over time for different methodologies.

Cost of Robotic Technology

While rTKA is a useful tool, it comes with steep costs. A study tracking 6 high-volume TKA surgeons over 2 years reviewed the costs of TKA per case. On average, direct cost per case for rTKA was $11,615 while mTKA costs $8,674 (calculated excluding preoperative imaging, labor, acute stay, and supply/implant cost)[27]. While cost of rTKA was higher, 30-day readmission rate was only 1.2% with rTKAs but 4.9% for conventional TKAs[27]. Importantly, the authors acknowledge readmissions were likely confounded by greater utilization management exposure in rTKA cases, which predominantly occurred after the removal of TKA from the "inpatient only" Medicare/Medicaid list. In many cases, hospitals or ambulatory surgery centers purchase robotic systems for surgeons and, as stakeholders, will expect a return on investment as the robot depreciates over time.

Case volume is an important factor in offsetting the cost. One study reported that, with a low annual volume of TKA (≤10 cases), the total loss is $71,025 for each case[43]. This cost is reduced to $7,463 per encounter when performing a moderate volume of TKAs (~100 cases/yr). A high volume of TKA (≥200 cases/yr) was associated with the lowest cost per encounter at $3,931[43]. Greater case numbers spread out costs, making recuperation easier. Robotic TKA maintains cost-effectiveness, according to the authors' model, if annual revision rates remain less than 1.6% at 1 year and quality-of-life measures remain favorable (on a scale derived from converted short form-36 scores and other quality-of-life measures)[43]. Future follow-up >10 years may allow a comprehensive cost-benefit analysis accounting for revision-free survival.

The largest cost in implementing rTKA is the cost of the robot itself. Surgeons and stakeholders new to rTKA may obtain cost estimates from their regional sales representatives. Many practices or hospitals enter into negotiated payment agreements with vendors or arrange payment strategies involving rebates. The terms of these contracts are highly variable and usually confidential. Case volume or rebate-based payment agreements can significantly influence a practice's implant choice. Purchase decisions should be considered in the context of a practice's planned rTKA volume and, for closed systems, comfort using the vendor's implants.

The estimated prices of each system are summarized in Table I[7,24,44,45]. Of note, new production of TSolution-One in the US market has recently been discontinued due to the upcoming release of a new active system. Aftermarket purchase of robots and replacement parts is possible, though little information is available in this regard.

There is marketing value in advertising of rTKA, although this should be balanced with setting reasonable patient expectations. A recent study using Google Trends open-source analytics showed patient interest in rTKA online is outpacing interest in conventional TKA[46]. A retrospective analysis from the Geisinger Health System demonstrated a modest increase in total TKA and UKA (17% and 190%, respectively) volumes and a slight shift toward more UKA after introducing and marketing rTKA[43]. This study also found robotic TKA was, on average, $176 more expensive per case than mTKA, though it did not capture postdischarge care utilization.

Given these costs, there are large disparities in rTKA access across geographic and socioeconomic patient populations. Many robots are currently in use at larger hospitals with greater capital. This results in lower accessibility for Americans with more comorbidities, those in predominantly White rural regions, or minorities in urban regions[47,48]. According to the New York statewide reporting system, rTKA was more often used in patients with private insurance over Medicaid (5.9% vs. 2.2%) and at high-volume hospitals[49]. These trends underscore a broader lapse in accessibility of medical technology for lower socioeconomic status patients. Minimizing cost and ensuring equitable access to rTKA are important goals for surgeons implementing rTKA.

Operative Time and Efficiency

When implementing robotic TKA, there is a learning curve for the entire surgical team. Another downside to rTKA is added surgical time compared with mTKA[29,37,45]. Increased case duration is primarily from added steps for computer guidance, resection planning, and robot setup[50,51]. Song et al. found rTKA increased operative time by a mean of 25 minutes[10]. Newer robot iterations have streamlined their user interface, tray organization, and instrumentation for efficiency.

Studies on rTKA adoption consistently show a learning curve for surgical time[52-54]. In one study using ROSA, mean operative time during the learning phase was 114 ± 17 minutes, decreasing to 110 ± 20 minutes during the proficiency phase ($p = 0.53$). A multicenter study using the Stryker Hospital

TABLE I Summary Table of Discussed Robots*

Robot (Vendor)	Platform	Type	Estimated Price (USD)	Guidance Method	Resection Method	Imaging	Safety Measures	FDA 510 (k) Status
CORI (Smith & Nephew)	Closed	Semiactive	500,000	Optical	Handheld burr	None	● Retracting optically tracked burr	TKA + UKA (2020), Revision TKA (2022)
MAKO (Stryker)	Closed	Semiactive	1,000,000	Optical and image	Robotic arm with saw	CT	● Haptically bound arm	TKA + UKA (2015)
ROSA (Zimmer-Biomet)	Closed	Semiactive	700,000	Optical and image	Handheld saw and robotic arm with cut block	XR or MRI	● Arm with cut blocks bound to single plane ● Cut verification tools	TKA (2019), UKA (2021)
Velys (Smith & Nephew)	Closed	Semiactive	No data	Optical	Robotic arm with saw	None	● Haptically bound arm ● Optically tracked saw	TKA (2021), UKA (2024)
TSolution-One (THINK Surgical)	Open	Active	650,000-800,000	Optical	Robotic arm with milling tool	CT	● Virtual boundaries ● Force and motion sensors	TKA (2024)
TMINI (THINK Surgical)	Open	Cut-block holes only, semiactive	No data	Optical	Manual	None	● Virtual boundaries ● Stereotactic guidance	TKA (2023)

*TKA = total knee arthroplasty and UKA = unicompartmental knee arthroplasty. Listed prices are based on publicly available manufacturer suggested retail price data from vendors or distributed vendor publications. Note that retail and maintenance contract prices vary widely and often negotiated in the purchase agreement between the vendor and hospital or practice. Disposables cost around $1,000 per case, but this also varies by system[7,25,40,41,80].

Reported Outcomes database calculated mean operative times (first incision to wound closure for mTKA vs. rTKA) and found time neutrality was achieved after 15 to 20 cases for most surgeons, with high-volume surgeons requiring only 7 cases[53]. One-third of surgeons were unable to achieve time neutrality after 20 cases, but later achieved this. Studies did not find a difference in early complications upon adoption of rTKA[52-54].

Turnover time is also affected by introduction of a new technology. Surgical personnel new to rTKA have a general dissatisfaction with turnover time since it adds new trays, equipment, and processes that may need troubleshooting. One study reported a turnover time of 72 minutes across 20 robotic cases, which represented a small increase from their baseline[55]. The largest contributors were cleaning of extra equipment, followed by instrumentation setup and retrieval of the patient from preoperative holding[55]. One group studied their implementation of a new robot using a task allocation and sequencing model borrowed from Formula One racing. They observed a decrease in turnover time from 99.2 to 53.2 minutes after 3 months, very close to their mTKA time[56]. Surgeons perceived increased room setup time as the main hindrance to efficiency while support surgical staff perceived instrument availability and processing time as main contributors. Interestingly, the perceived time delays exceeded the actual recorded increases documented by the independent researchers. An efficient workflow and retention of rTKA trained staff minimize turnover time[56].

Complications Specific to rTKA

Pin-Site Fractures and Infections

Bone pin placement is an integral part of rTKA that provides fixation for tracking arrays or other attachments. These can be placed intraincisionally or extraincisionally. Pins introduce a small risk of pin-site fractures and infections[18,25,57]. A systematic review found fracture rates between 0.06% and 4.8%[57,58]. Interestingly, none required revision surgery or open reduction and internal fixation. Another study reported the use of bicortical diaphyseal pins caused 3 femur fractures requiring intramedullary nailing (0.19%) in 1,571 TKAs[59]. The authors had 0 fractures when switching to unicortical pins (stopping pin advancement upon feeling contact with the far cortex). Some surgeons advocate metaphyseal pins since the bone is broader and the same-size holes introduce relatively smaller stress risers[57,58,60]. Metaphyseal pins can be placed intraincisionally but require a slightly larger incision and careful placement so as to not interfere with cutting or implant positioning. Pin size has also been implicated in fracture risk, and some surgeons advocate 3.2-mm over 4.5-mm diaphyseal pins. Smaller diameter metaphyseal unicortical pins seem to safely minimize fracture risk. However, these changes may provide weaker purchase in osteopenic bone.

Infection can occur at extraincisional pin sites, which presents as persistent drainage or delayed wound healing[18,25]. This could lead to osteomyelitis if untreated. The rate of pin-site infection was 0.5% in an 839-patient study[25]. The authors reported that all were successfully treated with topical antibiotics without subsequent recurrence, consistent with other studies. One study investigated whether pin diameter influenced infection risk and found no association[60]. Use of intraincisional pins eliminates this concern.

Iatrogenic Soft-Tissue Injury

Neurovascular injury, while a risk factor of TKAs, is a very rare occurrence. A study compiled a total of 39,990 TKAs from 1998 to 2013 showing 65 nerve injuries as a direct result of the procedure[61]. When comparing manual with rTKA, the same sources of injury exist. Certainly, femoral nerve or popliteal artery injury risk from tracking pin placement can be inferred from studies on external fixation[62]. Haptic controls and less aggressive resection tools theoretically provide added protection in rTKA. However, there are no large studies directly comparing rates of neurovascular injury between rTKA and mTKA to date.

The authors of a prospective comparison study found a lower rate of intraoperative iatrogenic soft-tissue and bony injury in 30 rTKAs compared with 30 mTKAs. They attribute this to reduced need for soft-tissue release and less overall bone resection in the robotic group[63]. Another prospective randomized controlled trial compared serum cytokine levels pre and postoperatively after patients underwent MAKO or CORI TKA vs. mTKA. The authors found decreased serum C-reactive protein ($p = 0.004$), interleukin-6 ($p < 0.001$), and tumor necrosis factor-alpha ($p = 0.021$) levels at postoperative day 7 with rTKA[64]. Levels were no longer different by day 28. The authors also hypothesized thiwas due to less soft-tissue release with rTKA, leading to less inflammation and postoperative pain, consistent with other data[64,65].

Blood Loss

Minimizing total blood loss is a core principle of surgery. Some authors argue rTKA increases blood loss due to increased case duration. A small study compared 50 robotic TKA vs. 50 mTKA patients and found a 23.7% decrease in blood loss and relative risk of transfusion with rTKA ($p < 0.01$ and $p = 0.02$, respectively)[66]. The same study compared robotic UKA with manual UKA and found no difference in blood loss or transfusion risk[66]. The authors attribute these differences to more tissue releasing and intramedullary drilling in mTKA. Another retrospective review of primary rTKA vs. conventional TKA found no difference in hemoglobin change or transfusions[67]. Overall, blood loss is a function of hemostatic technique, case duration, tourniquet use, and tranexamic acid administration rather than robotic use.

Increased tourniquet use may cause greater postoperative pain, greater deep vein thrombosis risk, slower rehab, and nerve injuries of varying severity[68-71]. Increased surgical time may translate to greater inflation time depending on how one chooses to deploy the tourniquet. One comparison study found no difference in tourniquet-attributed complications between mTKA and rTKA groups despite a small increase in tourniquet time (96.8 vs. 91.6, $p < 0.001$), which equalized during the final 20 of 148 rTKAs[51]. There is a general trend toward tourniquet-free TKA to avoid these complications entirely.

Comparison of Each System

This section is summarized in Tables I and II.

Guidance Method

With the exception of TSolution-One, the other systems use optical tracking for computer guidance. The optical tracking

TABLE II OR Footprints of Each Robot*

Robot	OR area (m^2)	Weight (kg)
CORI	<1 m^2 (single camera tower with display)	Tower: <80 kg
MAKO	1.5 m^2 (robotic arm, camera tower, separate display station)	Total: 460 kg
ROSA	1.42 m^2	Robot arm: 320 kg
	• Robot arm: 150 cm tall, 65 × 120.5 cm (0.78 m^2)	Tower: 140 kg
	• Camera tower with display: 84.5 × 76.1 cm (0.64 m^2)	
Velys	0.85 m^2	Satellite station: 107 kg
	• Camera tower with display: 206 cm tall, 81 × 56 cm (0.45 m^2)	Tower: 90.7 kg
	• Satellite station (w/arm attached): 156 cm tall, 71 × 56 cm (0.40 m^2)	
	• Detachable robotic arm: 0.22 m^2	
TSolution-One	• ~1 m^2 (~6 ft tall)	Unknown
TMINI	<1 m^2	Unknown

*Information was obtained from vendor distributed publications. All of these systems require a level surface for proper function. Most can be adjusted to minimize occupied space for storage. Manufacturers have specific instructions regarding necessary space/conditions[21,72,78,80,81].

systems are very accurate but rely on consistent visualization of arrays by the camera. A key challenge is ensuring the line of sight between the arrays and camera around staff or retractors. TSolution-One holds the knee in fixed flexion (recommended between 110° and 120°) via stabilizing pins and clamps, avoiding the need for optical tracking. A resultant limitation is inability to incorporate flexion and extension laxities into the virtual model[24]. The surgeon must manually assess pre and postresection soft-tissue balance. In addition, some patients may be unable to achieve the desired degree of flexion to use TSolution-One.

The MAKO and TSolution-One require preoperative fine-cut CT scans with a designated robotic protocol. ROSA has the options of preoperative radiograph, MRI, or imageless guidance. No studies comparing ROSA's accuracy with each method have been published. CORI and Velys, on the other hand, are imageless systems, relying solely on intraoperative mapping, saving cost and radiation. Image-guided or imageless options may be released for most systems in the future.

Resection Method

Resection is accomplished using different methods in each system with various available workflows. No cutting jigs or blocks are used with the MAKO, as cut planes are virtually defined by the computer, restricting the arm's motion to those planes[72,73]. The Velys robot uses a very similar system with virtual boundaries and haptics[74].

By contrast, the ROSA features a haptic bound robotic arm attached to a slotted cutting block with tight tolerance[75,76]. This special guided block also has holes for guided drilling of pins. The surgeon first performs distal femoral resection with a handheld saw through the guided block. The robot positions the block again to drill holes for a traditional 4-in-1 cut block. Surgeons have the option of using the robotic block to either make the tibial cut directly or drill holes for manual tibial cut block placement. This system also has an optional femoral rotation tool and tensioning instrument. In this workflow, the robot will assess the flexion gap based on the surgeon's tensioner adjustment (similar to conventional gap balancing) and suggest a femoral component rotation that would match the extension gap. The robot positions the guided cut block to drill holes for a 4-in-1 block[76,77].

CORI is distinct in its use of a haptic enabled and optically tracked handheld burr connected to the computer via a cord[78,79]. Resection can take longer with a burr compared with saws, but this allows greater freedom of motion. There are several resection options with the CORI. The distal femur cut is always completed using the burr. The surgeon can then choose to finish the remaining cuts with the burr alone or use guidance to burr holes for a conventional 4-in-1 block. Tibial resection can be entirely performed with the burr, but some elect to burr a flat "shelf" of bone and finish with a tibial cut block aligned with that shelf[79].

The TSolution-One uses an autonomous milling tool, similar to the CORI burr, which is attached directly to a robotic arm[24]. The entire resection must be completed autonomously by the computer-guided resection arm. This step may take longer than the other robots since all resection must be precisely performed. Surgeons do have the option of overriding the autonomous resection and using haptic-bound manual resection.

Unfortunately, no head-to-head comparison studies on final alignment and cut accuracy of each robot have been published.

Safety Measures

Added safety is a quoted benefit of robotic TKA. There is a paucity of studies comparing injury risk of individual robots. All the discussed systems provide visual, haptic, and auditory feedback to the surgeon to ensure resection does not move off the plane. This means locking of mechanisms inside the resection arm (for the

ROSA, MAKO, Velys, and TSolution-One) or retracting the resection tool (CORI) when excess motion or force is detected. Virtual boundaries created by the computer also help ensure soft tissues are protected, serving as a "guard rail." For MAKO and Velys, the "tightness" of these boundaries can be adjusted. All the semiactive systems give real-time visual feedback to the surgeon with color schemes representing optimal and excess resection depths[72,74,79,80].

In all the above systems, retractors should still protect key structures. In particular, the patella, patellar tendon, and collateral ligaments are not incorporated into virtual models. Thus, surgeons must take care to prevent errant cuts or destabilizing injuries.

FDA Approval

FDA approval is another important variable to consider, especially for new surgeons. Any cross-manufacturer implant use for closed systems is considered off-label in today's environment. Of note, CORI is currently the only FDA-cleared system for revision TKA, partly because it is imageless. Image-guided revision is challenging due to metal artifact and image distortion on CT or MRI, although artifact reduction protocols can help. In CORI revision TKA, the initial implant's surface is registered as if it were the native joint surface and the desired resection depth is set based on the underlying remaining bone surface. The burr resects bone to the desired depth, creating flat surfaces, and augments are figured into the plan by adjusting implant position in the virtual model until balance is achieved. The surgeon then implants components accordingly. Conversion of UKA or revision with any of the other robots is currently off-label use. Other vendors are devising technologies to expand into revision rTKA as well.

Operating Room Space

Having a robot that is too large for an OR can create difficulties with turnover times and transferring between rooms. When positioning personnel and retractors, smaller spaces compound difficulties with ensuring a clear line of sight between the camera and optical arrays. The footprints of discussed robots are summarized in Table II.[24,72,78,80,81]. CORI and TMINI were designed with a minimal footprint to help minimize line-of-sight obstructions.

Future of Robotic TKA

Vendors are actively competing to improve their robots by integrating new technologies. Many vendors have introduced augmented reality headsets, which project a user interface onto transparent displays in front of the eyes. By incorporating an optical tracking camera into the headset itself, augmented reality may eliminate line-of-sight difficulties and camera/display towers. Another important emerging technology is artificial intelligence in TKA. Machine learning can, in theory, allow a personalized approach to TKA by making specific recommendations based on patient characteristics. Although more concrete and reliable data are required before computers can be trained to make useful predictions, rTKA allows collection of the necessary data[2,82]. Rudimentary models are already being developed to predict value metrics after TKA[82]. Surgeons should pay close attention to this technology moving forward.

Summary

The systems explored here comprise the majority of the US rTKA market in 2024. Each robot offers distinct guidance and resection strategies to achieve a desired plan. While adopting robotic TKA can seem daunting, this article aims to provide a condensed overview for guidance. Surgeons may face unique obstacles or prioritize different variables in this endeavor. Perhaps, the largest change surgeons may face when switching to rTKA is implant restriction with closed systems. Currently, TSolution-One and TMINI are the only open platforms available in America.

The current arthroplasty market has met robotics with cautious optimism. New data are constantly being collected regarding the efficacy and limitations of rTKA. Moreover, cost is a significant driver in today's financially strained healthcare market and the true value proposition of rTKA remains to be fully determined. Subsequent improvements in robotics will likely have a deep impact on the future of arthroplasty. ■

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