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INSTRUCTIONAL REVIEW

Comparative assessment of current robotic-assisted systems in primary total knee arthroplasty

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Abstract

Robotic-assisted total knee arthroplasty (TKA) has proven higher accuracy, fewer alignment outliers, and improved short-term clinical outcomes when compared to conventional TKA. However, evidence of cost-effectiveness and individual superiority of one system over another is the subject of further research. Despite its growing adoption rate, published results are still limited and comparative studies are scarce. This review compares characteristics and performance of five currently available systems, focusing on the information and feedback each system provides to the surgeon, what the systems allow the surgeon to modify during the operation, and how each system then aids execution of the surgical plan.

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Introduction

Primary total knee arthroplasty (TKA) is a highly successful treatment. It is both clinically effective and cost-efficient.[1] Continuous developments in implant design, materials, and surgical techniques have been successful in improving long-term prosthesis survival rates, functional outcomes, and overall satisfaction for patients.[2] Although the ideal prosthesis alignment is still a point of debate, there is consensus about the importance of the impact of limb alignment and implant positioning.[3,4] In attempts to maximize accuracy of the bone preparation and subsequent prosthesis alignment, several computer-assisted surgery (CAS) systems have been designed as adjuncts to TKA.[5-7]

CAS systems in TKA. CAS systems can be divided into different categories based on their involvement in the procedure: passive, semi-active, or active.[8] Computer navigation is the predominant type of passive CAS used in TKA. The surgeon keeps direct control over the procedure, while the passive CAS has a supporting role. Navigation can provide feedback about alignment, range of motion (ROM), and the orientation of the bony cuts. After a surge in the 1990s, popularity dwindled, and the lack of clinical impact shown by its use, together with the added cost, led to this technology being abandoned by many. Semi-active and active systems are controlled robotic tools where specific tasks are either guided or executed by the CAS, respectively with or without the surgeon's direct intervention.

To summarize, where navigation assists the surgeon to perform the procedure with more accuracy by the information it provides, a robotic system will additionally offer physical assistance in the execution of bone preparation. This difference sets robotic-assisted TKA (rTKA) apart from other, passive CAS systems.

Comparison of systems. With several robotic systems competing for a market share, the aim of this review was to compare them using objective criteria. Each system was assessed by examining the following aspects: the information provided by the CAS; the ability to modify the plan during the procedure; and the accuracy of execution of the surgical plan.

The five systems compared were: TSolution One (THINK Surgical, USA), which is active and partially autonomous; the MAKO SmartRobotics Robotic Arm Interactive Orthopaedic system (Stryker, USA), a semi-active robotic arm-assisted CAS system; the ROSA Knee system (Zimmer-Biomet,

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Table I. Summary of discussed characteristics of computer-assisted surgery systems. No objective measure for accuracy of the different systems is currently available. A star-based ranking was used, ranging between ★ and ★★★, as explained in Table II.

Variable	MAKO	CORI	ROSA	TSOLUTION ONE	OMNIBotics
Type	Semiactive	Semi-active	Semi-active	Active	Semi-active
Input					
Base	CT + mapping	Imageless, pure mapping	Imageless or plain film radiographs + mapping	CT + mapping	Imageless, pure mapping
Mapping	Handheld probes (sharp + blunt)	Handheld probe	Handheld probe (blunt)	Machine-connected RA	Handheld probe (blunt)
Dynamic info	Femur/tibia arrays	Femur/tibia arrays	Femur/tibia arrays	N/A	BalanceBot integrated gap analysis
Variability					
Planning	Preoperative	Only intraoperative	Pre- and intraoperative	Preoperative	Only intraoperative
Ability to adapt	✓	✓	✓	N/A	✓
Implant	Brand restricted	Brand restricted	Brand restricted	Implant database/open platform	Brand restricted
Output					
Soft-tissue balance	Laxity pre- and post-cut	Laxity pre- and post-cut	Laxity pre- and post-cuts	N/A	Laxity pre- and post-cut
Measured resection	✓	✓	✓	✓	✓
Functional alignment	✓	✓	✓	N/A	✓
Execution					
Execution	RA	Handheld	RA (jig) + manual	RA automatic	Patient-mounted robotic controlled cutting jig
Accuracy	★★★	★★	★	★★★	★
Soft-tissue protection	Haptic feedback / virtual boundaries	Smart burr / virtual boundaries	Handheld saw	Autonomous burring	Handheld saw
Footprint	> 1 m^2	0.5 to 1 m^2	> 1 m^2	>1 m^2	0.5 to 1 m^2
Estimated cost (MSRP in USA$)	1,000,000	500,000	700,000	800,000	400,000

MSRP, manufacturer's suggested retail price; N/A, not available; RA, robotic arm.

Canada), a semi-active robotic arm-assisted CAS system; the CORI Surgical System (Smith & Nephew, UK), a handheld semi-active CAS system; and the OMNIBotics (Corin, Circencester, UK), a cutting jig-based robotic system mounted to the patient's knee.[9-12]

The VELYS Robotic-assisted Solution (Depuy Synthes, Johnson & Johnson, USA), a semi-active robotic arm-assisted CAS system, has recently been launched.[13] Although it has received FDA approval in the USA, it is still awaiting CE marking. As such it was not available for comparison and was not considered by this review.

The different characteristics of these robotic systems are summarized in Table I.

What does the robot tell you? Similar to other computer algorithms, these robotic systems rely on specific data input. Data acquisition is an important aspect in which the systems differ. Both the MAKO system and the TSolution One require a preoperative CT scan of the patient's knee. In both cases, these are segmented, converted to a 3D model, and used as the basis for the operative plan. Intraoperatively, additional mapping with a handheld or a robotic arm mounted probe are used to produce a navigated map of the knee which is then surface-matched to the CT.[9,12] The need for additional preoperative imaging can be seen as both an advantage and a disadvantage. The potential gain in accuracy by giving the CAS more precise input stands against the added cost of the investigation, the processing, and the additional exposure to ionizing radiation. Using plain film radiographs instead of CT imaging potentially lowers the cost and the exposure to radiation, as seen in the ROSA system with the option of converting a 2D radiograph to a 3D model as the basis for planning. Although the ROSA system offers this image-based option, it can function completely imageless, similar to the CORI system and OMNIBotics. These CAS systems both rely on intraoperative mapping of the knee and its surfaces with handheld probes to produce a virtual 3D model of the operated knee.[10,11] Whether preoperative imaging is used to build a 3D model or not, the navigated surface point registration or mapping remains crucial to achieve the desired level of accuracy.

In addition to the static 3D model of the knee these systems use, they (with exception of the TSolution One) offer the possibility of adding dynamic data to the model.

With the use of femoral and tibial mounted optical arrays and the use of mapped landmarks, the hip's centre of rotation and knee axes are calculated. All systems use a three planar model with separate vectors for femur and tibia. An assessment of the knee's alignment and its stability under valgus or varus stress through the ROM provides dynamic data that adds a virtual representation of the soft-tissue envelope to the bone-based model. The acquisition of this dynamic data is a point of criticism as most systems, with the exception of the OMNIBotics,

Table II. Explanation of the star-based ranking system used as a visual representation of the accuracy of the different robotic systems, seen in Table I.

Level of accuracy	Influencing factors	Visual representation
High	Robotic arm mounted cutting tool Haptic feedback Virtual boundaries OR fully active computer-assisted surgery	★★★
Medium	Handheld bone preparation tool Virtual boundaries	★★
Low	Robotic controlled cutting jig Manually controlled saw	★

Table III. Summary of the number of studies reporting on clinical outcome for each of the systems. These numbers resulted from a PubMed search on 31 August 31 2022, using the terms 'Robot-assisted', 'Robotic' AND 'Total Knee Arthroplasty', 'TKA'.

	MAKO	NAVIO/CORI	ROSA	TSOLUTION ONE	Omnibotics
Published outcome	48	26	8	12	10

use manually applied stress to assess stability, combined with the difficulty of reliably applying varus or valgus stress with deeper flexion, as rotation in the hip mitigates these forces. Contrary to the other systems, the MAKO only captures virtual gap data in full extension and 90° of flexion, relying as it does on the use of a single radius femoral component.

All systems give continuous feedback to the surgeon via visual output on screen. The CORI and ROSA offer a touchscreen that can be draped for the surgeon to use during the operation. An additional foot pedal helps the surgeon navigate through the different steps of the workflow. Despite this, a designated product specialist is often needed to operate the console and give assistance. The visual output itself differs between manufacturers and offers graphs and plots to show the dynamic properties of the joint as well as 3D models of the knee, with representation of the bony cuts and the position of the implants.

What does the robot let you modify? The TSolution One is the only fully active CAS system currently on the market. Its robotic arm autonomously mills the bony surfaces as it executes a preoperatively determined plan. Information about the dynamic properties of the operated knee and its soft-tissue envelope is a prerequisite for gap balancing and functional alignment goals in TKA. As such, the TSolution One only offers the option for a measured resection-based execution of a preoperatively determined plan based on the patient's bony anatomy. In contrast, the other systems allow the surgeon to plan and adapt during the procedure. They offer the option of altering the bone cut orientation to balance the knee intraoperatively, rather than relying on measured resection only. This allows the surgeon to react to changes to the joint's balance caused by removal of osteophytes or the effect of cutting the posterior cruciate ligament on flexion gap in posterior-stabilized TKA systems. Furthermore, tibial component slope and femoral component flexion and rotation can have a significant effect on the overall balance of the knee. No matter what the alignment goal is, the aim remains to give the patient a well-fixed, properly sized, positioned, and balanced TKA in the belief that this will function well and result in high patient satisfaction.

The TSolution One is the only robotic system on the market offering the surgeon an implant library to choose from. The other CAS systems are closed platforms and offer no inter-brand compatibility. This exclusivity could be considered a potential limitation to the end user.

How does the robot execute the plan? Robotic CAS systems were conceived to improve accuracy and reduce outliers when compared to conventional jig-based TKA. All systems have proven accuracy over and above that produced by conventional instruments. Based on the design or operating method of each CAS system, a difference in accuracy can be expected. Direct comparisons of the different systems are not available. Accuracy of the different robotic systems is the result of multiple factors and highly dependent on certain design and set-up choices. Because of the nature of this outcome and the multiple factors influencing it, a star-based ranking system has been employed to rate accuracy (Table II).[14]

The ROSA helps the surgeon to accurately position the cutting jigs on the bone of the patient. The actual preparation of the bony surfaces, however, is performed by a manually operated oscillating saw. In the other systems, the burr or saw is guided by virtual boundaries set by the 3D model of the knee. The MAKO aims to improve accuracy using a robotic arm-mounted saw or burr, with haptically controlled virtual boundaries. Because the CORI does not use a robotic arm, but a smart burr, its accuracy is determined by optical navigation. The smart burr has two modes of operation, where the burr either stops or retracts once the surgeon deviates outside the boundaries. Although the femoral and tibial optical arrays try to give constant feedback about the position of the leg on the table, not all movement artefacts can be detected by the system due to limitations in the refresh rates of the optical systems. If an error is observed or exceeds a threshold, the systems all prompt extra checks or recalibration. The TSolution One intends to minimize these movement artefacts further by physically attaching the patient's femur and tibia to the device.

The different approach of each system has its effect on potential soft-tissue damage too.[15] In all cases, the surgeon remains responsible for appropriate positioning of the retractors and protection of the soft-tissues. As mentioned above, the ROSA features manual preparation of the bone and one can therefore expect similar risks to the soft-tissue envelope. The other systems use virtual boundaries. Instead of stopping the burr or saw like the MAKO, the CORI slows down or retracts the burr when the boundaries are reached.

The adoption of these systems in a surgeon's practice comes at a cost. In addition to the obvious financial cost of acquiring a robotic system, their use can prove to be time-consuming as well, including the preoperative planning phases and the extra intraoperative steps when compared to conventional jig-based TKA.[16] The console and camera need setting up and need additional draping. For the optical arrays, as well as for the fixation rods in the TSolution One, separate stab incisions are made in the upper and lower leg. To assure accuracy, calibration of the device is needed before and often during the procedure. As described above, mapping of the joint surfaces and registering landmark points are needed to accurately match the patient's knee with the virtual model in the CAS system.

The option of executing the complete plan in one go in some systems, like the TSolution One and MAKO, allows surgeons to make up for at least part of the lost time by removing the need to reposition cutting jigs.

Ease of use is a highly subjective feature that tends to improve as a surgeon progresses through the learning curve. This should allow the surgeon to further minimize the additional cost in operating time. The mean procedure duration should level out after a certain number of cases as the learning curve reaches a plateau.[17] However, different studies use different outcomes to evaluate the learning curve and so direct comparisons are problematic.

There exists a potential paradox between the premise of making low-volume surgeons more accurate and those same surgeons' difficulty in doing sufficient numbers of cases to climb the learning curve.

The financial cost is more obvious and therefore more often used as an argument against the adoption of CAS systems. As discussed above, the cost of preoperative planning and imaging needs to be taken into account for some systems. The cost to acquire the robotics system itself depends on the sales model used by the manufacturer. Estimated retail prices reveal the most expensive system of those compared to be the MAKO. With a retail price of around US$1 million, it is almost twice the investment compared to the CORI. Without a physical robotic arm, however, one could argue that the CORI is an evolution of previous navigation systems rather than a true robotic aid. Both the ROSA and the TSolution One are less expensive than the MAKO.

Extending the list of procedures is a potential strategy to help justify the overall cost of acquiring a robotic system. Most systems offer unicompartmental knee arthroplasty (UKA) in addition to TKA. Application in total hip arthroplasty (THA) is available with (MAKO) and under development for other systems (CORI).

However, because we lack data about revision rate and longevity, the overall cost-effectiveness is almost impossible to calculate at this stage.[18,19]

Clinical results. Although highly effective, with proven cost-efficiency and good long-term survivorship, TKA still has inferior functional outcomes and patient satisfaction when compared to total hip arthroplasty.[1] Manually positioned alignment jigs and cutting blocks combined with handheld bone resection make accurate implant positioning, ligament balancing, and preservation of the soft-tissue envelope highly dependent on the surgeon's experience and skill level. These surgeon-controlled variables imply a poor reproducibility, higher risk of soft-tissue and bone damage, and potentially negative effect on patient satisfaction, functional outcomes, and implant longevity in conventional TKA.[20]

As with all new technology, outcome data, especially with long-term follow-up, remains scarce so far. Despite this, rTKA has already shown improved accuracy and reduced alignment outliers in numerous in vitro and in vivo studies.[21-27] The patient-specific operative plan is executed with more precision, improving bone coverage and limb alignment.[21,27] The dynamic data provided by the MAKO, CORI, OMNIBotics, and ROSA systems additionally allow for better gap balancing and ligament tensioning. Semi-active systems like MAKO or CORI have also demonstrated reduced iatrogenic bone damage and periarticular soft-tissue injury because the sawblade or burr action is limited and guided within virtual boundaries.[20]

Consequently, reduced postoperative soft-tissue swelling was observed in studies comparing rTKA versus conventional TKA.[15] Furthermore, another study observed reduced postoperative pain, decreased analgesia requirement, shorter time to quadriceps reactivation, and increased ROM at discharge when compared to conventional TKA.[28]

These effects have in turn resulted in significantly improved pain, patient satisfaction, and physical function scores during the first six months after surgery.[29] However, less evidence exists for the same effect on medium- and long-term outcomes.[30-32]

In the limited number of studies comparing different robotic systems to each other, no significant superiority has been shown of one system over another. Table III shows an overview of the number of studies reporting on the clinical outcomes for the different systems.

Conclusion

Evidence exists for the ability of robotic surgical aids to reduce alignment outliers and improve accuracy when compared to manual instruments in TKA. The short-term postoperative results also show significant improvement. Compelling evidence of their cost-effectiveness or the superiority of one system over another is, however, still lacking. Each system has its strengths and limitations.[33]

The overall adoption of robotic systems, and the number of cases performed with them, is increasing, which will inevitably lead to an increase in the number of publications reporting on their long-term results. Beyond the currently available results, the adoption of technology like robotic assistance will provide the means to test different alignment theories in a robust manner, ultimately allowing a better understanding of the ideal patient-specific alignment goals. In turn it is hoped that this will allow patients to achieve better clinical outcomes, justifying the expense of robotic aids in routine care.

Take home message

- In this paper, the authors give a thorough overview of the currently available robotics systems used in total knee arthroplasty.
- Given the fact that this technology is gaining ground rapidly across the globe, a comparative review like this will provide readers with a useful and insightful reference article.

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