Robotic technology in total knee arthroplasty

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Abstract

Key factors for successful total knee arthroplasty include accurate implant positioning with precise tibial and femoral resection, combined with appropriate soft tissue balancing to achieve the desired alignment. Robotic-assisted total knee arthroplasty allows surgeons to execute pre-planned strategies with precision, with growing evidence suggesting that robotic-assisted-total knee arthroplasty reduces radiological outliers. This has yet to be proven to translate into long-term improvements in patient-reported outcomes and implant survivorship. Robotic-assisted-total knee arthroplasty systems can be divided into fully autonomous and semi-autonomous systems. While fully autonomous systems showed initial promise, semi-autonomous systems are gaining popularity with encouraging early outcomes suggesting improved radiological and clinical outcomes, although concerns remain regarding a significant learning curve, installation costs, radiation exposure and cost associated with preoperative imaging. The future of total knee arthroplasty seems certain to involve robotic technology, although to what degree and in what capacity will depend on further high-quality studies assessing long-term outcomes, complications, survivorship and cost–benefit analyses.

Key words: Arthroplasty; Knee; Outcomes; Robotic; Survivorship

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Introduction

Total knee arthroplasty remains one of the most commonly performed surgical procedures worldwide, with over 100000 cases performed annually in the UK alone (before the COVID-19 pandemic) (National Joint Registry, 2020). While total hip arthroplasty has been described as the operation of the century owing to its excellent patient satisfaction of greater than 90% at 10 years (Learmonth et al, 2007; Ramaskandhan et al, 2021), knee arthroplasty yields slightly inferior results (Rodriguez-Merchan, 2021). Although the optimal alignment principle in total knee arthroplasty continues to be a topic of debate (Haddad, 2017; Roussot et al, 2020), key factors for a successful knee replacement include accurate implant positioning with precise tibial and femoral resection, combined with appropriate soft tissue balancing to achieve the desired alignment, with minimal damage to the surrounding soft-tissue envelope (Devers et al, 2011; Khan et al, 2016; Abdel et al, 2017). With increased awareness of arthroplasty as a treatment option and the majority of patients reporting high satisfaction rates, the number of total knee arthroplasties performed continues to rise. The average age of a patient undergoing total knee arthroplasty is falling (Kurtz et al, 2009) and with even higher functional expectation and demands placed on the implant, the need for precision with bony resection, implant positioning and ligamentous balancing is of utmost importance for patient satisfaction and implant survival.

Recent technological advancements, including robotically-assisted total knee arthroplasty and three-dimensional printed patient-specific implants and instrumentation, focus on optimising these surgical factors. Navigation in total knee arthroplasty is well-established and the underlying principle allows surgeons to assess the patient's osseous anatomy on a live-screen intraoperatively to accurately perform bony resection and ligament balancing. Previously, in the UK and USA between 3 and 5% of total knee arthroplasties performed have used navigation, whereas notably in Australia rates are higher at 30% (Picard, 2014). Navigated total knee arthroplasty relies on conventional jig-based methods to perform bony resections. More recently robotic total knee arthroplasty has built on the principles of navigation aiming to allow surgeons to execute preoperative plans with greater accuracy with the help of an intraoperative robotic arm. Depending on the type of robot, the arm will either execute the predetermined resections or will assist the surgeon in doing so (Song et al, 2013; Hampp et al, 2019; Sultan et al, 2019).

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Robotic-assisted total knee arthroplasty is a rapidly developing field and while the potential applications of robotic technology in total knee arthroplasty have generated considerable interest and investment, concerns remain related to cost, the learning curve, and limited evidence comparing long-term outcomes with those of conventional total knee arthroplasty techniques. This article summarises the current status of robotic technology in total knee arthroplasty, discusses its benefits and limitations, and evaluates the latest evidence relating to outcomes compared to conventional total knee arthroplasty methods.

Types of robotic total knee arthroplasty

Robot-assisted total knee arthroplasty can broadly be divided into fully active/autonomous and semi-active/autonomous systems. Table 1 illustrates key features of common robotic systems.

Fully active/autonomous

Fully active systems use preoperative data (in the form of a computed tomography or magnetic resonance imaging scan) combined with intraoperative anatomical mapping to perform pre-planned bony resections autonomously. ROBODOC, now known as TSolution-One (THINK Surgical Inc., Fremont, California, USA), is a well-known example of a fully active system. This system uses a preoperative computed tomography scan to create a virtual model on which the surgeon can plan bony cuts to achieve the desired alignment, implant positioning and sizing (Liow et al, 2017a). The surgeon performs the approach and positions soft tissue retractors in a standard manner, but must place the leg in a customised foot and thigh holder as well as applying stabilisation pins into the femur and tibia which connect to a frame. This avoids the need for intramedullary femoral canal instrumentation. The surgeon proceeds to identify different anatomical landmarks on the femur and tibia which are registered, allowing the robot to match the preoperative imaging and surgical plan

Table 1. Comparison of common robotic total knee arthroplasty systems

Robotic system	TSolution-One	Mako Robotic Arm Interactive System	Navio Surgical System	CORI Surgical System	Rosa Knee System	VELYS Robotic-Assisted Solution	OMNI-Botics knee system
Company	THINK Surgical Inc. (Fremont, CA)	Stryker Ltd, (Kalamazoo, MI, USA)	Smith and Nephew, (Andover, Texas, USA)	Smith and Nephew, (Andover, Texas, USA)	Zimmer-Biomet, (Warsaw, Indiana, USA)	DePuy Synthes, (Warsaw, IN, USA)	Corin, (Cirencester, UK)
Type	Fully autonomous	Semi-autonomous	Semi-autonomous	Semi-autonomous	Semi-autonomous	Semi-autonomous	Semi-autonomous
Imaging	Computed tomography	Computed tomography	Imageless	Imageless	Imageless or plain X-ray	Imageless	Imageless
Planning	Preoperative	Preoperative	Intraoperative	Intraoperative	Pre- or intraoperative	Intraoperative	Intra-operative
Execution	Robot-led burring	Robotic arm with saw, surgeon-controlled	Handheld burr	Handheld burr	Robot-assisted cutting jig, handheld saw	Robotic arm with saw, surgeon-controlled	Robot-assisted cutting jig, handheld saw
Soft tissue protection	Robot-led burring, override button for emergency deactivation	Virtual and haptic feedback, saw cut-out beyond boundaries	Virtual feedback, burr cut-out beyond boundaries	Virtual feedback, burr cut-out beyond boundaries	Surgeon controlled, handheld saw	Saw cut-out outside resection plane but no mechanical boundary control	Surgeon controlled, handheld saw

to intraoperative reference points and confirm the accuracy of the virtual model created. The surgeon is then able to activate the robot which autonomously completes the femoral and tibial bony resections, although the surgeon has control of a manual override button for emergency deactivation should the need arise.

Outcomes and limitations

Fully active or autonomous systems have had somewhat limited uptake compared to semi-active systems, partly as a result of mixed outcomes described in the literature. Song et al (2013) performed a randomised trial of 100 patients and found the robot-assisted group had no mechanical axis outliers (> ±3° from neutral) compared to 24% in the conventional group. They found no difference in postoperative range of motion or Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores (minimum 3-year follow up), but noted an increased operative time (25 minutes) in the robot-assisted group. Similarly, Liow et al (2014) randomised 60 patients and found the robot-assisted group had no mechanical axis outliers and no cases of notching, compared to the conventional group which had 19.4% deviation from the mechanical axis (> ±3°) and 10.3% notching. They also assessed joint line restoration and found the robot-assisted group had only 3.23% joint line outliers (>5 mm) compared with 20.6% in the conventional group (Liow et al, 2014). In a follow-up study, they assessed 2-year outcomes in the same group of patients that had been randomised to robot-assisted or conventional total knee arthroplasty. They reported that the Knee Society Scores, Oxford Knee Scores and patient satisfaction rates were not significantly different between the two groups, although the robot-assisted group had slightly improved quality of life scores compared to the conventional group (Liow et al, 2017b).

Limited data currently exist on long-term outcomes, but Yang et al (2017) retrospectively assessed 113 patients and found similar clinical outcomes (visual analogue scale pain score, Hospital for Special Surgery score, Western Ontario and McMaster University score, range of motion and complications) and revision rates between the robot-assisted and conventional groups at a mean 10-year follow up. They noted no difference in the average radiological outcomes, but found a significant reduction in radiographic outliers (> ±3°) in the robot-assisted group, consistent with previous studies.

Concerns with fully autonomous systems have centred on high installation costs, a learning curve associated with higher complications, increased radiation exposure, longer operating and tourniquet time and soft tissue injury (Liow et al, 2017a). Liow et al (2017a) found an average tourniquet time of 91 minutes and noted 6.5% of patients in their robot-assisted group developed deep vein thrombosis, which they attributed to the leg being held rigidly in the foot-thigh holder. In a large randomised controlled trial with 10-year follow up (724 knees), Kim et al (2020) found the robot-assisted group had a longer tourniquet time (75 vs 38 minutes), which remains a commonly-held concern for robotic total knee arthroplasty. The robot-assisted group contained fewer radiological outliers (> ±3°) and no difference in clinical outcomes were recorded between the two groups. There was no difference found in survivorship or complications. Learning curve was not assessed as the surgeon had performed 30 robot-assisted total knee arthroplasties before the study.

Park and Lee (2007) randomised 72 patients to fully active robot-assisted vs conventional total knee arthroplasty, and found a higher complication rate in the robot-assisted group, including one superficial infection, one patellar tendon rupture, one dislocation of the patella, one postoperative supracondylar fracture, one patellar fracture and one peroneal injury in early cases. While fully active systems have shown superior radiological outcomes than conventional total knee arthroplasty, reports of complications during the learning curve and significant set-up cost have limited their widespread use. Current robotic systems do not detect soft tissue and thus concerns of violation of surrounding soft tissue structures, for example patella tendon injury as described by Park and Lee (2007), have likely contributed to the increasing popularity of semi-autonomous systems, which provide the surgeon with a greater degree of control.

Semi-active systems

Semi-active systems give the surgeon a greater degree of control over the femoral and tibial resections. They can be image-guided (with preoperative radiographs or computed tomography) or imageless, and allow the surgeon to control the bony resections while providing live on-screen visual, and in some cases haptic, feedback to ensure accurate execution of the preoperative surgical plan.

The Mako Robotic Arm Interactive System (Stryker Ltd, Kalamazoo, MI, USA) is an image-guided semi-active system which was approved by the Food and Drug Administration in 2016 (Pailhé, 2021) (**Figure 1**). Using a preoperative computed tomography scan, a virtual three-dimensional model is created and the surgeon is able to plan femoral and tibial resections, implant positioning, alignment and sizing. The leg can be held in a mobile holder and can be manipulated to provide the desired exposure. The digital model is validated by intraoperative referencing of bony landmarks. The robotic arm is then positioned and controlled by the surgeon to execute the bony resections, with the robot preventing the saw from moving beyond the pre-defined resection zones providing a degree of protection to the surrounding soft tissues (Kayani et al, 2018a). Before making the definitive bony cuts, flexion and extension gaps can be dynamically assessed using computer navigation, allowing the surgeon to perform measured soft tissue releases to ensure balanced gaps, and also adjust the planned bony resections if required (Khlopas et al, 2018).

The Navio Surgical System (Smith and Nephew, Andover, Texas, USA) is another example of a semi-active system. This does not use a robotic arm, rather it uses a hand-held platform to perform pre-planned bony resections with visual but no haptic feedback. The surgeon controls the burr but, as with other semi-active systems, the reamer will stop if it is detected to have passed beyond the predefined boundaries of resection. This is an imageless system and does not require preoperative computed tomography, saving the patient significant radiation exposure. Intraoperative mapping and referencing of anatomical

Figure 1. Mako robotic arm interactive system (Stryker Ltd, Kalamazoo, MI, USA).

landmarks are performed in a similar fashion to that described for other robotic total knee arthroplasty systems to create a virtual three-dimensional model of the patient's knee to allow planning of bony resection and implant positioning.

An update of the Navio Surgical System is the CORI Surgical System (Smith and Nephew, Andover, Texas, USA). While sharing the same fundamental features as the Navio system, CORI has a smaller theatre footprint, an improved burr which delivers an increased cutting volume and an upgraded tracking system that provides a faster refresh rate (Sicat et al, 2021; Smith and Nephew, 2023). These changes aim to provide faster intraoperative anatomical registration and faster burring, which early evidence suggests may reduce overall operative time (Sicat et al, 2021).

A newer, potentially imageless system is the Rosa Knee System (Zimmer-Biomet, Warsaw, Indiana, USA). The system uses preoperative X-rays, although an imageless option is available. Following intraoperative mapping of anatomical landmarks and insertion of the femoral and tibial reference pins, a surgical plan is created and a robotic arm allows accurate positioning of the cutting blocks to facilitate the planned resections. The surgeon will handle the saw and complete the resections independently but can verify the accuracy of the cuts and symmetry of flexion and extension gaps using the on-screen computer navigation. Unlike some other systems, the ROSA Knee System is compatible with a number of commonly used implants, giving the surgeon a greater degree of flexibility with implant choice. This is particularly beneficial for surgeons and theatre teams who are familiar with or only have access to specific implants. Early evidence suggests the system can achieve accurate bony resection, with Rossi et al (2023) demonstrating no significant difference between the angles of planned and measured cuts in 75 patients.

One system gaining popularity is the OMNIBotics knee system (Corin, Cirencester, UK). This is an imageless system which, similar to many other navigation systems, creates a three-dimensional model of the patient's knee via placement of tibial and femoral pins, and intraoperative referencing of bony landmarks (Shatrov et al, 2021). The surgeon plans the desired bony resections and implant alignment with the help of the software, and intraoperative soft tissue and gap balancing can be assessed using the system's soft tissue balancing tool (BalanceBot). This provides on-screen visual representation of the gaps and alignment throughout the range of motion of the knee, and soft tissue release or adjustments to bony resections can be made accordingly. Two different robotic cutting blocks are positioned on the femur and tibia. The guides then allow the surgeon to perform bony resections according to their desired plan and the surgeon retains full control in handling the saw.

The VELYS Robotic-Assisted Solution (DePuy Synthes, Warsaw, IN, USA) is an imageless system available in the USA and the UK. The system relies on intraoperative anatomical landmark mapping and data acquisition using femoral and tibial arrays and reference pins. A surgical plan is created intraoperatively and a bed-mounted robotic arm is used to perform bony resections. The VELYS system will ensure the plane of resection is maintained and is designed to stop the saw if it moves out of the resection plane. However, there is no mechanical boundary control of the saw blade and the surgeon must ensure that there is no surrounding damage to soft tissue structures (Doan et al, 2022). Although this is a new system, early evidence in cadaveric studies supports its ability to improve alignment accuracy and reduce radiological outliers compared to conventional total knee arthroplasty (Doan et al, 2022).

Outcomes and limitations

While it is too early for long-term clinical data to be collected on semi-active robotic total knee arthroplasty systems, there are sufficient early data to suggest their benefit in achieving precise bony resection, improved radiological outcomes and reduction in potential soft tissue injury (Kayani et al, 2018a; Marchand et al, 2018). Marchand et al (2018) reported a case series of 330 semi-active robot-assisted total knee arthroplasties which included 129 patients with severe varus and seven patients with severe valgus deformity (defined as 7° or greater deformity). All patients achieved within 2° neutral alignment, demonstrating the potential for robot-assisted total knee arthroplasty to assist surgeons in correcting significant coronal plane deformity.

Kayani et al (2019) compared 60 semi-autonomous robot-assisted total knee arthroplasties with 60 conventional total knee arthroplasty procedures performed by a single surgeon and assessed radiological outcomes, implant positioning and alignment, operative times and surgical team anxiety levels. They found robot-assisted total knee arthroplasty produced greater accuracy with final implant positioning and alignment compared to the conventional group with reference to preoperative plans. The desired femoral/tibial sagittal and coronal alignment, tibial slope, and joint line restoration were all more accurately achieved in the robot-assisted total knee arthroplasty group (Kayani et al, 2019). The operative time significantly improved after the initial learning curve which was identified to be seven cases. Average operating time in the first seven cases was 89.2 minutes; this decreased to an average of 66.8 minutes for the subsequent 53 robot-assisted total knee arthroplasty cases. This is only slightly greater than the average of 62 minutes for conventional jig-based total knee arthroplasty in this study. Their study suggests the learning curve for reducing operative time may be shorter than previously suspected. The learning curve for achieving the desired alignment has also been shown to have two distinct phases, an initial learning phase followed by a consolidation phase; in their single surgeon case series of 204 patients, Pannu et al (2021) found a much greater learning curve of 110 patients in achieving the desired alignment in robot-assisted total knee arthroplasty.

Figueroa et al (2019) assessed the accuracy of the OMNIBotics knee system by analysing 173 cases to compare the intra-operative recorded position of the implants with postoperative computed tomography scans. They found the OMNIBotics system to be highly accurate with regards to femoral coronal alignment and tibial coronal alignment, with a mean difference between navigation and computed tomography values of 0.1° and 0.7° respectively. In the sagittal plane the accuracy was reduced, with only 75% of patients having a tibial sagittal alignment value within 2° on the computed tomography and robotic systems. When the tolerance was increased to a 3° difference between computed tomography and navigation, that figure rose to 93%. While there are limited data on patient-reported outcomes, a series of 766 cases reported 99.48% survivorship of the implants at 6-year follow-up (Shatrov et al, 2021).

Early outcomes from semi-active systems are promising, when compared to conventional total knee arthroplasty. Marchand et al (2017) assessed 6-month patient satisfaction, pain and physical function scores in 20 robot-assisted total knee arthroplasties vs conventional total knee arthroplasties. Using the WOMAC patient satisfaction outcome survey, they found the robot-assisted total knee arthroplasty group had significantly greater satisfaction scores. Furthermore, the mean pain score was significantly lower and the physical functional score was significantly higher in the robot-assisted total knee arthroplasty group. Comparing 80 consecutive robot-assisted total knee arthroplasties with 80 conventional total knee arthroplasties, Marchand et al (2023) reported improved reduced-WOMAC scores and physical function scores at 2-year follow up.

Mitchell et al (2021) compared 139 manual total knee arthroplasties with 148 consecutive robot-assisted total knee arthroplasties performed by a single surgeon and found no difference in the Knee Injury and Osteoarthritis Outcome Score for Joint Replacement and the University of California at Los Angeles activity score at 1-year follow up. However, they did note that the robot-assisted total knee arthroplasty group had a significantly shorter length of stay (1.18 vs 1.73 days), reduced opiate requirement and fewer physiotherapy visits (11 vs 13) than the manual total knee arthroplasty group.

Mahoney et al (2022) assessed 1-year patient-reported outcome measures in 143 robot-assisted total knee arthroplasties and 86 conventional total knee arthroplasties, and reported improved Veterans RAND 12-item health survey (VR-12) physical component scores and qualitatively greater Knee Society composite functional scores in the robot-assisted total knee arthroplasty group. Kayani et al (2018b) similarly found a reduced time to discharge (77 vs 105 hours), reduced requirement for postoperative analgesia, decreased number of physiotherapy sessions and shorter time to straight leg raise when comparing 40 robot-assisted total knee arthroplasties with 40 conventional total knee arthroplasties in a single surgeon study. While short-term radiological, clinical and functional outcomes from semi-autonomous systems for total knee arthroplasty are encouraging, long-term data are still awaited.

As mentioned, one concern with fully autonomous systems relates to the potential for surrounding soft tissue injury given the surgeon does not directly control the movement

Key points

- Robotic total knee arthroplasty systems are gaining in popularity and aim to allow the surgeon to execute a pre-planned strategy with a high degree of precision.
- A wide range of robotic systems exist, including fully autonomous and semi-autonomous systems.
- Early evidence suggests improved radiological outcomes for semi-autonomous robotic total knee arthroplasty compared to conventional total knee arthroplasty.
- There is currently weak evidence to suggest significant mid-term improvement in patient-reported outcome measures with robotic total knee arthroplasty.
- Long-term data on differences in patient-reported outcome measures implant survivorship between robotic and conventional total knee arthroplasty are awaited.

of the saw blade or burr. Semi-autonomous systems may overcome this by providing visual and haptic feedback as the surgeon completes the desired cuts. Khlopas et al (2017) compared semi-active robot-assisted total knee arthroplasty with conventional total knee arthroplasty in cadaveric knees to assess ligamentous injury and found no injury to the posterior cruciate ligament, medial collateral ligament or lateral collateral ligament in the robot-assisted total knee arthroplasties. The robot-assisted total knee arthroplasty cases did not require tibial subluxation which may contribute to reduced ligamentous stretching and injury. Prospective randomised trials have suggested that early local inflammatory responses may be reduced in robot-assisted total knee arthroplasty compared with conventional total knee arthroplasty, and this may facilitate faster rehabilitation (Kayani et al, 2021; Fontalis et al, 2022).

Given the significant variation in robotic systems' characteristics, and the growing number of systems available, it is important that going forward each system is appraised individually and generates its own evidence base.

Conclusions

Robotic total knee arthroplasty systems aim to allow the surgeon to execute a pre-planned strategy with a high degree of precision, with a growing body of evidence suggesting robot-assisted total knee arthroplasty can reduce radiological outliers with good early clinical outcomes. This has yet to be proven to translate into long-term improvements in patient-reported outcomes and implant survivorship, which will require several years to be accurately adjudicated. There is currently weak evidence that robot-assisted total knee arthroplasty results in superior mid-term patient-reported outcome measures. Semi-autonomous systems are gaining popularity although concerns remain with regards to a significant learning curve and increased operative time during the learning phase, high installation costs, additional radiation exposure and cost with preoperative computed tomography imaging, and additional incisions and registration pins.

The future of knee arthroplasty surgery seems certain to involve robotic technology, although to what degree and in what capacity will depend on further high-quality studies assessing long-term outcomes, complications, survivorship and cost-benefit analyses.

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Conflicts of interest

The authors declare that there are no conflicts of interest.

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