MENTORS IN ORTHOPEDICS

ROBOTIC KNEE SURGERY: WHAT'S IN A NAME?

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AUTHORS

Jan Victor - Hôpital Universitaire de Gand, Gand, Belgique
Hannes Vermue - Hôpital Universitaire de Gand, Gand, Belgique

SUMMARY

Background: Robotic-assisted total knee arthroplasty (TKA) has seen rapid clinical adoption driven by technological advancements, evolving alignment philosophies, and industry marketing. Despite this growth, the transition from conventional surgical navigation to robotic platforms necessitates a critical evaluation of their technical utility, cost-effectiveness, and clinical efficacy.

Objective: This review aims to analyze the current landscape of robotic knee surgery by examining the various technological architectures, levels of intraoperative assistance, and the clinical implications of integrating these systems into orthopedic practice.

Key Points: Robotic systems are categorized by their reliance on preoperative imaging (CT/MRI) versus intraoperative mapping, with image-based platforms offering superior rotational landmark definition and boundary control. Mechanical assistance ranges from autonomous bone resection to haptic-guided or passive boundary systems. While robotics may enhance precision and soft-tissue protection, significant challenges remain regarding the reliability of intraoperative gap analysis and the lack of standardized data collection. Current literature is characterized by a high prevalence of financial conflicts of interest and a lack of long-term, industry-independent randomized controlled trials. Furthermore, while a learning curve exists for surgical efficiency, most platforms are currently restricted to specific implant brands, impacting their broader cost-effectiveness.

Conclusion: Robotic technology in TKA offers potential improvements in component positioning and soft-tissue preservation; however, current systems possess inherent technical limitations. Future advancements require independent clinical validation and improved integration of real-time ligament balancing to translate technical precision into superior long-term patient outcomes.

KEYWORDS

Arthroplasty, Replacement, Knee; Robotics; Surgery, Computer-Assisted; Treatment Outcome; Knee Joint

INTRODUCTION

Robotic knee surgery has grown exponentially over the past few years. This remarkable surge was boosted by several drivers. The remarkable achievements of new technology in different technical domains affected marketing in all aspects of society and certainly helped robotic surgery to gain traction. The growing awareness in and beyond the orthopaedic community on the outcome of knee arthroplasty being far from perfect also served as an open invitation to technological aids. New insights in lower limb alignment intrigued surgeons, who started looking at different options to position the implant relative to the native anatomy of the patient. The ambition to reliably tweak the long-standing alignment paradigms by a few degrees could only be realised by more precise control of the bone cuts. Finally, direct to consumer (patient) marketing by the orthopaedic industry and orthopaedic surgeons proved to be a powerful tool to attract more patients.

All these events happened in a time span of about five years and changed the field of total knee arthroplasty in many ways. As the dust of the initial bang is settling a little, it is time to take a critical look at this technology.

WHAT DO WE UNDERSTAND UNDER THE TERM "ROBOTIC KNEE SURGERY"?

Robotic knee surgery did not come out of the blue. Intra-operative feedback systems were developed in the nineties of the previous century and were called "Surgical navigation". These systems informed the surgeon on three-planar alignment, knee laxity and range of motion, and proved to be precise in the coronal plane [4]. Sagittal plane precision was somewhat inferior, but the real problem was the rotational alignment [3, 16, 17]. Right from the start image-based technology was developed but computing power was insufficient to guarantee a fluent surgical workflow [25]. Later on, sensors were developed (VERASENSE® (Stryker, Michigan, USA), giving the surgeon feedback on the forces that act upon the knee joint in a passive setting.

The so called 'Surgical robots' add another feature and all assist in some way with the making of the bone cuts. It would hence seem logical to define a surgical robot as a feedback tool that can also physically assist the surgeon in making the bone cuts. The different levels of assistance will be discussed further in this text. In addition to giving feedback and physically assistance, robots can also gather data on the surgical workflow, the final alignment of the limb, knee stability and range of motion.

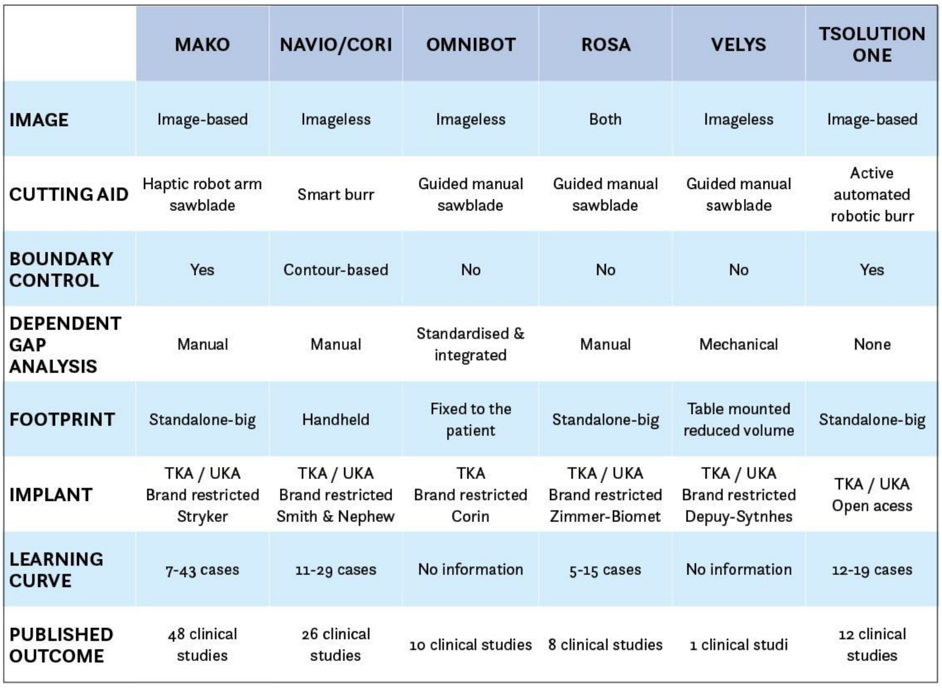
WHY WOULD WE NEED ROBOTICS IN THE OPERATING ROOM?

Asking this question to residents and experienced colleagues often leads to the same answer: "To enhance precision". On second thought however, this is only part of the answer. A higher precision could perfectly be achieved with the latest generation of surgical navigation systems [13] and given the fact that these systems failed to realise a significant market penetration, this cannot be the only gain in using a far more expensive robotic machinery. One of the primary tasks of robotic systems should be to help the surgeon find the optimal position for the components, to achieve the best possible alignment and stability for the patient, knowing that this will always be an imperfect surgical compromise. A less visible, but in our view important potential advantage, is the protection of the soft tissues. Recent research has shown that surgeons with oscillating saws inflict more damage to the soft tissues than desirable [6, 9].

The argument of data collection is often quoted, but little has come out so far. Privacy and legal barriers can prevent the dissemination of data and their use in artificial intelligence (AI) applications. One can also question how precisely the final position of the femoral and tibial component can be derived from the bone cuts that are known to the system. Positional changes do occur during insertion of the final components, be it cemented or cementless [2]. The holy grail in closing the loop is obviously finding the relation between alignment and stability data on one hand and final outcomes of the procedure on the other hand. One should not forget however that these postoperative alignment and stability data are obtained in a patient who is supine, anaesthetised and obviously not weight bearing, and that outcome data are often missing, incomplete or unreliable. As promising this pathway is, many hurdles and practical obstacles appear on the road to success. Predictive analytics and personalised, data driven surgical solutions sound hip and sexy but remain distant targets as of today.

ARE ALL ROBOTIC SYSTEMS CREATED EQUAL?

No. There are major differences between systems that are on the market today. Table 1 shows a graphical overview of currently used robotic knee systems. They are characterised on the following parameters: Imageless versus Image-based, Level of cutting aid, Presence of boundary control, Availability of dependent gap analysis, Footprint, Brand restriction of the implant, Learning curve and Published outcomes. We did not include the cost of the systems as all companies use different strategies based on purchase or leasing, local market penetration, volume of implants used, and local pricing of competitors.



	MAKO	NAVIO/CORI	OMNIBOT	ROSA	VELYS	TSOLUTION ONE
IMAGE	Image-based	Imageless	Imageless	Both	Imageless	Image-based
CUTTING AID	Haptic robot arm sawblade	Smart burr	Guided manual sawblade	Guided manual sawblade	Guided manual sawblade	Active automated robotic burr
BOUNDARY CONTROL	Yes	Contour-based	No	No	No	Yes
DEPENDENT GAP ANALYSIS	Manual	Manual	Standardised & integrated	Manual	Mechanical	None
FOOTPRINT	Standalone-big	Handheld	Fixed to the patient	Standalone-big	Table mounted reduced volume	Standalone-big
IMPLANT	TKA / UKA Brand restricted Stryker	TKA / UKA Brand restricted Smith & Nephew	TKA Brand restricted Corin	TKA / UKA Brand restricted Zimmer-Biomet	TKA / UKA Brand restricted Depuy-Sytnhes	TKA / UKA Open acess
LEARNING CURVE	7-43 cases	11-29 cases	No information	5-15 cases	No information	12-19 cases
PUBLISHED OUTCOME	48 clinical studies	26 clinical studies	10 clinical studies	8 clinical studies	1 clinical studi	12 clinical studies

Imageless versus Image-based

The debate on imageless versus image-based applications is still ongoing. The most important disadvantage of imageless systems is the lesser accuracy in the definition of geometric axes and planes as compared to image-based systems. Coronal plane accuracy is satisfactory for both imageless and image-based platforms, but the reported inaccuracies in the identification of rotational landmarks for both femur and tibia that surfaced during the evaluation of surgical navigation equally affect imageless robotics [7, 16, 17]. Rotational landmarks can far better be defined with the use of Image-based systems [24]. Image-based systems need to justify the extra cost for the Magnetic Resonance Imaging (MRI) or Computed Tomography (CT) scan and the radiation risk in case of the use of a CT scan [1]. Imageless systems need some extra time intra-operatively for marking the relevant landmarks, although the technology has become significantly faster over the past 2 years. Image-based technology requires pre-operative planning. Although AI or off-site engineers can suggest a surgical plan, control by the operating surgeon is highly desirable, and adds up to the total time of the procedure. Boundary control is more feasible with image-based systems and is discussed further in the text.

Level of cutting aid

As stated before, assistance in making the bone cuts is a characteristic feature of knee surgical robots. The level of assistance and tools to make the cuts are different.

The highest level of mechanical assistance is the autonomous robot, which makes the cuts without manual help of the surgeon. The surgeon only supervises the procedure and guards an emergency stop button. THINK Surgical is offering this option with the TSolution One (THINK Surgical, California, USA). The cuts are made with a high-speed burr and the limb of the patient is rigidly fixed to the robot.

The next level of assistance is Haptic control, as offered by MAKO (Stryker, Michigan, USA). With this technology, the surgeon operates the oscillating saw. The robotic arm guides the surgeon in the correct plane and produces increasing resistance as well as visual control in case the surgeon deviates from the planned resection area and cutting depth. The VELYS (Johnson & Johnson, New-Jersey, USA) system is supplying correct planar positioning of the oscillating saw, and visual control on-screen, but no haptic resistance.

A so called ‘smart burr’ is a different technology to assist in making the bone cuts. With this technology, the surgeon operates a high-speed burr that retracts or stops in case the surgeon deviates from the planned resection area. The CORI (Smith & Nephew, London, UK) system is using this technology. Visual on screen control is also offered with this technology.

The lowest level of cutting assistance is provided by systems that position a cutting slot for guidance (OMNIBot (Corin, Circencester, UK) and ROSA (Zimmer-Biomet, Indiana, USA)). In this case, the surgeon still has to make the cut with the oscillating saw, without mechanical control of the robot on the saw. Strictly speaking, these devices should be called augmented navigation systems.

Boundary control

As previously explained, boundary control can best be achieved based on a preoperative image acquired by CT or MRI scan. This is more difficult, if not impossible with imageless technology as the contours of the bone are not exactly known. The superficial geometry of distal femur and proximal tibia is transferred to the system intra-operatively, just after the exposure of the joint and before the bone cuts are made. Hence it is difficult to reach the posterior aspect of femur and tibia with the pointer. The systems try to overcome this difficulty with the use of anatomical libraries to match the individual anatomy of the patient as close as possible. Boundary control is also easier to obtain with haptic control or a smart burr. In case the surgeon is using an oscillating saw with only a cutting slot as a mechanical guidance, chances of damaging the soft tissue are greater. Visual and audio warning can offer extra information but there is no mechanical safety guard.

Dependent gap analysis

Most orthopaedic surgeons use a surgical technique that is based on a combination of measured resection and dependent gap analysis. It is during this step in the surgical procedure that robotics and AI have a great potential to increase accuracy and help the surgeon to determine the optimal position of the implant for the individual patient. The indispensable requirements to integrate dependent gap analysis into robotic systems are three-fold: the ability to track position of femur and tibia simultaneously in real time, the use of a reliable system to tension the ligaments and measure the gaps, and finally the option to adapt the pre-operative plan intra-operatively.

The fully automated robot offered by THINK Surgical approaches the femur and tibia independently and is purely based on measured resection principles. MAKO, CORI, ROSA and VELYS require manual stress to assess the gaps. The problem with this approach is the paradox of combining highly precise and expensive technology with manual tests that are prone to high variability and different forces, failing to yield reproducible measurements. In addition, manually stressing the knee joint becomes awkward beyond 45° of knee flexion as hip rotation mitigates the varus and valgus forces that can be applied to the knee joint. The rotation of the femur often puts the reference frames in a position where they lose line of sight with the camera. These limitations render the assessment of the gaps unreliable in our view.

The combination of the good old tensioners with robotic systems is a potential upgrade but has a strong perfume of a DIY solution: instead of using the technology as an integrated system, you perform the task by yourself. The only system that has a full integration of dependent gap analysis is the OMNIBot. It allows an assessment of the gaps during full range of motion with standardized forces that can be independently applied to the medial and lateral compartment. Potential flaws are the impact of the weight of the system on the outcomes, the influence of friction on the paddles during the measurement cycles and the influence of manually controlled limb position [15].

Footprint

Many surgical rooms are overstuffed, and storage space is often problematic. The size of the systems and ease of transportation is an argument that is sometimes used in the decision-making process of buying or leasing. All systems have a significant footprint in size and weight, except for the CORI and the OMNIBot. The VELYS offers in this respect an in-between solution, with a robotic system that is mid-size and can be attached to the operating table.

Brand restriction

All systems except THINK Surgical are brand-restricted, meaning that they can only be used with a specific knee implant provided by the same manufacturer that also provides the knee robot. Certain legal arguments might play a role, but the dominating factor is the business model. In contrast to robotics in the field of urology or general surgery, the recurrent revenues are only marginally generated by the sales of disposables. The main income in the business of knee arthroplasty is generated by the sale of the implant. This model is considered in cost-effectiveness analyses on robot-assisted knee arthroplasty [12, 23]. This business model firmly seals the brand of robot and implant.

Learning curve

As with any new surgical technology, time is needed to develop sufficient experience and skills in order to work safely and effectively. This is called the surgical learning curve [21]. A fair evaluation of this learning curve with robotic systems should include a control with conventional instruments which also face a well-known learning curve. Experience of the surgical team is also needed to avoid lengthy robotic procedures that might induce additional complications [19]. As well, since robotic systems are capable to aid in the execution of a specific plan, the possibility to precisely reach the intended plan can reduce outliers, especially for younger or less experienced surgeons [22]. Nonetheless, conventional surgery should not be forgotten, as in (rare) cases of system malfunction, the surgeon might be challenged with the dilemma to abort the procedure and switch to conventional instruments.

Published outcomes

The number of clinical studies with published clinical, functional, or radiological outcomes varies between the different robotic systems. For example, in decreasing order, the MAKO (48 publications) is followed by the CORI (26 publications), TSolution One (12 publications), OMNIBot (10 publications), ROSA (8 publications), and VELYS (1 publication). The listed publications were recovered on the 31th of August 2022 (MEDLINE/PubMed with the terms ‘Robot-Assisted’, ‘Robotic’ AND ‘Total Knee Arthroplasty’, ’TKA’) and will quickly increase. Where the initial enthusiasm with the new technology can bias the early publication, we expect more Level 1 studies in the near future.

Specifically in the field of robotics, bias remains an important problem. As the financial impact of purchase or leasing of these robots is significant, a potential publication bias arises. It is unlikely that authors who convinced their hospital management to invest in these new technologies are inclined to publish disappointing results. In addition, many of the early adopters who currently provide the first publications helped in the development of the robotic systems, workflows and interfaces. As such, in 90% of the currently published literature, the authors have a financial conflict of interest, as shown by DeFrance et al [5]. The authors ask for more industry independent adequately powered RCTs to assess the comparative clinical benefit, revisions rates and long term survival of robotic versus conventional TKA surgery.

Surgical time

In most studies on robot-assisted total knee arthroplasty, regardless of the type of system used, more time is required to perform the surgery compared to the conventional technique. Although, some studies on the MAKO, NAVIO/CORI and TSolution One platforms have shown the possibility to reach surgical times without any statistical significant difference to the conventional procedure [10, 11, 14, 18, 22]. Important to note is that these studies handle the skin-to-skin time. Often not reported in clinical studies is the set-up time of the robotic system, which happens prior to skin incision [8, 20]. The time required to set up the system should be stated more clearly in future studies, as it unequivocally influences the total time the operating theatre is unavailable for other surgeries.

CONCLUSION

New technology is often over-estimated in the short term but under-estimated in the long term. Most surgeons and companies believe that robotics in knee surgery is here to stay. All systems that are currently on the market have flaws and shortcomings, and the aim of this text is not to rank the systems or choose a ‘winner’, but rather to present a critical analysis of the features that characterise these robotic systems. A fast progress of all technological aids on the market is expected in the short term. A close collaboration between surgeons, development engineers and companies will be needed to improve the systems and outcomes for our patients.

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