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Review

Robotic Systems in Knee Surgery: Current Concepts and Future Perspectives

Antonino Cantivalli [1,*], Umberto Cottino [2], Davide Edoardo Bonasia [2], Federica Rosso [2] and Roberto Rossi [2]

[1] ASLTO5, Department of Orthopaedics and Traumatology, Ospedale Maggiore di Chieri, Via Giovanni de Maria, 1, 10023 Chieri, Italy
[2] AO Ordine Mauriziano Hospital, Department of Orthopaedics and Traumatology, University of Turin, Largo Turati 62, 10128 Torino, Italy
* Correspondence: antonino.cantivalli@gmail.com

Abstract: Total knee arthroplasty (TKA) is a successful and highly effective procedure in most patients with tricompartmental knee arthritis. Despite the innovations in surgical techniques due to planning software and technological innovations, patients' dissatisfaction after TKA is still high, at up to 20%. Robotic-assisted surgery (RAS) could be considered as a future option for improving outcomes due to its higher accuracy, precision, and reliability. Robotic systems can be classified as fully active, semi-active, or passive depending on the surgeon's involvement during the procedure, and as imageless or image-based according to the necessity of radiological exams for the pre-operative planning. Three of the most well-known robotic systems for knee surgery are MAKO® (Stryker Ltd., Kalamazoo, MI, USA), NAVIO® (Smith & Nephew, Andover, TX, USA), and ROSA® (Zimmer Inc., Warsaw, IN, USA). These systems show differences in terms of surgeon involvement, the use of CT scans or X-rays for pre-operative planning, the possibility to perform both unicompartmental knee arthroplasty (UKA) and TKA (or even total hip arthroplasty THA), and in the different kinds of knee prosthesis that can be implanted. This article aims to describe the features of the most used robotic systems for knee arthroplasty, to examine their outcomes and analyze their cost-effectiveness, and to evaluate future perspectives.

Keywords: robotic-assisted surgery; TKA; MAKO; NAVIO; ROSA

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1. Introduction

Total knee arthroplasty (TKA) is a successful and highly effective procedure in most patients with tricompartmental knee arthritis [1]. The number of TKAs performed annually is constantly growing worldwide, and in the United States, it is supposed to increase by 143% by 2050 compared with 2012 [1–3]. Although the literature shows good implant survivorship [4,5], and despite the innovations in implant design, materials, planning software, and the introduction of patient-specific instrumentations (PSI), recent studies show that up to 20% of patients remain dissatisfied after TKA [6–9]. Different theories and studies have been elaborated to improve patients' satisfaction, focusing on implant positioning, alignment, and soft tissue balancing, which are all crucial variables affecting functional outcomes, implant stability, and long-term implant survivorship [8,10–15]. In this scenario, robotic-assisted surgery (RAS) may help in the planning and performance of surgery with greater precision, aiming to improve outcomes in TKA. Conventional jig-based TKA (cTKA) is based on pre-operative radiographs, intraoperative anatomical landmarks, and manually positioned alignment jigs to guide bone resections and implant positioning, with the risk of poor reproducibility, possible soft tissue iatrogenic injuries, and limited intraoperative data on gap measurements or ligamentous tensioning [15,16]. RAS, instead, uses computer software to convert anatomical information (CT scan, radiographs, or anatomic landmarks) into a virtual patient-specific three-dimensional (3D) reconstruction of the knee joint. This virtual model may be used to plan optimal bone resection, implant

positioning, bone coverage, and limb alignment based on the patient's unique anatomy. Subsequently, an intraoperative robotic device may help to execute the pre-operative patient-specific plan with high accuracy [15,17]. This article aims to describe the most frequently used robotic systems for knee arthroplasty, to examine their outcomes and analyze their cost-effectiveness, and to evaluate future perspectives.

2. Robotic-Assisted Surgeries: How Many Different Options?

The first robots in surgery were used in neurosurgery (1988) and prostate cancer surgery (1985) to guide biopsies. Since then, robotic surgery has been introduced in other surgical fields [18,19]. In 2002, the da Vinci Robot System® (Intuitive Surgical, Sunnyvale, CA, USA) initiated a new concept of robotic surgery, transforming both medical practice and learning [18,19]. In orthopedic surgery, the first available robotic system in TKA was Robodoc® (Curexo Technology, Fremont, CA, USA), introduced in 1992 [18,19]. Since then, technology's improvement has progressively modified surgery practice, and nowadays, two different branches can be described: computer-assisted (CAS) and robotic-assisted (RAS) surgery. CAS uses a computer system to obtain live on-screen information about patient anatomy and knee kinematics during surgery. CAS provides the surgeon with patient-specific anatomical data and indications for bone resection and optimal implant positioning, but the computer system does not actively intervene in the operation. All patient information on the knee joint may be obtained using pre-operative imaging such as CT scans (image-based navigation), intraoperative mapping of bony anatomical landmarks (non-image-based navigation), or both [18]. Conversely, RAS intervenes in surgery, improving accuracy through a robotic arm after creating a 3D model of the knee joint based on the patient's anatomical landmarks [8,9,17,20]. Depending on the surgeon's external control, the robotic arms are classified as passive, fully active, or semi-active systems [8,18]. Passive systems work under the continuous and direct control of the surgeon (CAS belongs to this category) [21]. Fully active robotic systems, instead, work autonomously to perform the femoral and tibial bone resections previously planned by the surgeon (i.e., ROBODOC®, Curexo Technology, Fremont, CA, USA) [18,19]. Particularly, the surgeon performs the surgical approach, places retractors to protect the soft tissues, and secures the limb to a fixed device, and finally, the robotic device executes the planned bone resections. However, the surgeon can check and control the robotic arm and deactivate it in case of emergency. Lastly, semi-active robotic systems allow the surgeon to control bone resection and implant positioning, receiving live intraoperative feedback about any deviation from the pre-operative surgical plan (i.e., NAVIO®, Smith & Nephew, Andover, TX, USA) [18,19]. The primary limits of this technology are related to initial costs and the increased risk of short-term complications during the learning curve (i.e., superficial infection, iatrogenic fractures, and common peroneal injury) [8]. Robotic systems can also be classified into "closed" or "open" platforms. The former can be used only with one specific implant, whereas the latter can be used with different implants and designs, depending on the surgeon's preference or the patient's demands. The three most commonly used robotic systems for knee arthroplasty are: MAKO® (Stryker Ltd., Kalamazoo, MI, USA), NAVIO®, and ROSA® (Zimmer Inc., Warsaw, IN, USA), the most recent one introduced on the market. MAKO® is a semi-active, CT-based, closed platform system, and it is the most studied robotic system in literature [19]. The system can be used to perform unicompartmental knee arthroplasty (UKA), total knee arthroplasty (TKA), and total hip arthroplasty (THA). The NAVIO® Surgical System is an imageless, semi-active, open-platform robotic assistant that uses a handheld device to map osseous anatomy in the operating room, and it guides bone resection only for UKA and TKA [19]. Finally, the ROSA Knee System® has recently gained the approval of the Food and Drug Administration (FDA). This semi-active robotic system converts two-dimensional knee radiographs into a 3D patient-specific bone model. It creates virtual plans on implant positioning and ligament balancing so that the surgeon may manually perform the bone cuts guided by the robotically positioned cutting blocks, according to a patient-specific plan [8]. In the next section, these three robotic systems are

described in detail, with related outcomes summarized in Table 1. Subsequently, other less used robotic systems are described, such as OMNIbotics® (Corin Ltd., Cirencester, UK) and CORI (Smith & Nephew, Andover, TX, USA).

Table 1. Summary of main features of the three robotic systems.

	MAKO® (Stryker Ltd., Kalamazoo, MI, USA)	**NAVIO® (Smith & Nephew, Andover, TX, USA)**	**ROSA® (Zimmer Inc., Warsaw, IN, USA)**
level of surgeon involvement	Semi-active	Semi-active	Semi-active
image-based	CT scan	Imageless	X-rays (imageless possible)
UKA or TKA	Both	Both	TKA
implant choice	Closed platform-KINETIS® implant system (MAKO Surgical Corp., Ft. Lauderdale, FL, USA), TRIATHLON® (Stryker Ltd., Kalamazoo, MI, USA	Open platform	Closed platform-Persona® (Zimmer Inc., Warsaw, IN, USA), Vanguard® (Zimmer Inc., Warsaw, IN, USA) and Nexgen implants® (Zimmer Inc., Warsaw, IN, USA)
workflows	1. Measured resections 2. Gap balancing	Only measured resection	1. Measured resections 2. Gap balancing 3. Hybrid
bone cuts	Saw directly assembled on the system	Saw or handheld burr	The surgeon holds the external saw, and the system controls the cutting guides.
approval date	2008	2012	2019

3. MAKO

3.1. Principles

MAKO®, or The Robotic Arm Interactive Orthopedic System, is a semi-active, CT-based, closed platform system, available in clinical practice for UKA, THA, and TKA, which was approved by the FDA in 2008 [19]. The MAKO® system works through a visual and haptic interface, which helps surgeons to perform knee (or hip) arthroplasty according to predetermined parameters set during the pre-operative plan in order to better reproduce knee alignment and protect essential soft tissue structures such as the medial collateral ligament, posterior cruciate ligament, and the neurovascular bundle [18,20–22]. The system requires the support of a dedicated clinical engineer to create a 3D model of the patient's anatomy (based on CT images) for pre-operative planning of bone resection, implant sizing, and implant positioning, as well as to identify anatomic landmarks (the trans-epicondylar axis, the posterior condylar axis, and the mechanical axis) and soft tissues along with the presence of osteophytes [17,19–23]. The 3D model allows for virtual pre-operative and intraoperative adjustments of the components' position based on alignment and ligament balancing information before performing the definitive bone resection [18,24]. Moreover, it is a so-called "closed platform", which is designed and set only for the Triathlon Total Knee System® (Stryker Orthopaedics, Kalamazoo, MI, USA) and the KINETIS® implant system (MAKO Surgical Corp., Ft. Lauderdale, FL, USA) [25].

3.2. Surgical Technique

3.2.1. Unicompartmental Knee Arthroplasty (UKA)

The MAKO® system can be used to perform both UKA and TKA in two phases: pre-operative planning and an intraoperative step. During pre-operative planning, the software and a dedicated engineer allow the surgeon to perform a virtual components' sizing and positioning according to different anatomical landmarks based on a 3D patient-specific knee model obtained from the CT scan (i.e., tibial spines, slope, posterior cruciate ligament (PCL) insertion, Blumensaat's line, trochlear lateral edge, etc.). Based on the surgeon's preferences,

the incision is the same as for a normal UKA. After placing both tibial and femoral trackers, anatomical landmarks and surface mapping can be registered. At this point, the osteophytes can be removed, and the surgeon is asked to register the stability of the knee in a minimum of four poses (extension 5–10°, mid-flexion 45°, flexion 90°, and full-flexion 100–120°, foot always in neutral rotation) while applying a valgus stress to correct the coronal deformity passively (for medial compartment arthritis). The intensity of the valgus stress should be enough to open up the collapsed medial compartment and to tension the medial collateral ligament (MCL) to achieve the desired degree of correction and joint stability, making sure not to overcorrect the deformity. For a lateral partial knee arthroplasty, the procedure is performed while applying a varus stress with the same principles. When all poses are registered, a gap balancing graph will show the joint stability for each captured flexion pose. The next step consists of mapping the cartilage through a blunt probe to place the virtual prosthesis components (bone registration). By slightly flexing or extending the knee, it is possible to set the correct position according to the load-bearing tracking shown by the system based on the 3D model derived by the fusion of the CT scan and bone registration phase (intraoperative planning). Once the joint is virtually balanced, and the robotic arm is correctly positioned, the bone resection is performed through a handheld burr controlled by the system, and the definitive implants are positioned. The patellofemoral joint (PFJ) procedure follows the same principles of CT-based planning and virtual positioning of the components except for the different bone landmarks registered during the pre- and intraoperative planning (i.e., Blumensaat's line, trochlear lateral edge, etc.) [24].

3.2.2. Total Knee Arthroplasty (TKA)

The pre-operative planning for TKA is the same as for UKA, using a patient-specific CT-based bone model projected by a dedicated engineer and virtual implant templates to size, align, and position according to the patient-specific anatomy. Once the robotic system and the patient are correctly positioned, draped, and prepared, a standard TKA surgical approach is performed according to the surgeon's preferences (i.e., standard anteromedial with parapatellar approach or anterolateral approach). After tibial and femoral array positioning, the software divides the procedure into four steps: bone registration, intraoperative planning, bone preparation, and case completion. The bone registration phase consists of patient landmarks and bone checkpoints, as well as registration/verification. The patient's landmarks are at the extreme ends of the limb, that is, at the hip center (registered by moving the lower limb circularly) and medial and lateral malleolus (captured through a probe pointed on the anatomical site). The bone checkpoints can be divided into femoral and tibial checkpoints (i.e., medial epicondyle, tibial anteromedial border). The bone registration/verification consists of collecting different points, which are critically important in setting the 3D virtual model and planning definition. During the intraoperative planning phase, the system can be set for a "measured resection" or "gap balancing" technique, offering the possibility to modify the position and eventually the size of the component on the 3D virtual model (obtained by the fusion of bone registration and the CT scan). A virtual balancing is then performed based on the software's load-bearing tracking, and the bone preparation phase can start (Figure 1).

In this step, the robotic arm activated directly by the surgeon performs the bone cuts without cutting blocks with an assembled saw. Graphically, the robotic system shows the correct amount of bone to resect in a green color, turning red if the bone cut is deeper than planned, with an associated vibration and locking of the saw (Figure 2).

At this point, the surgeon can test the joint laxity and ligament tension using a spacer block or trial components (depending on the chosen workflow), and the definitive component can be implanted [25]. In the "case completion" phase, the tibial and femoral mechanical checkpoints are removed before the definitive end of the procedure.

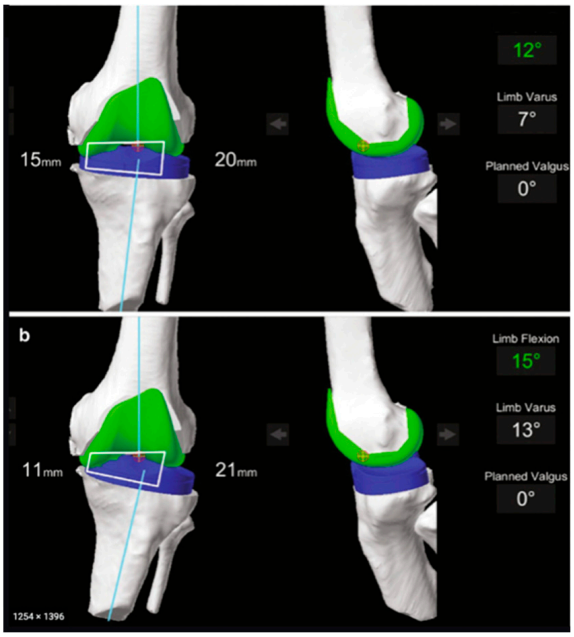

Figure 1. Example of the end of intra-operative planning phase with simulation of implant positioned. The femoral component is green colored, the tibial component is blue colored.

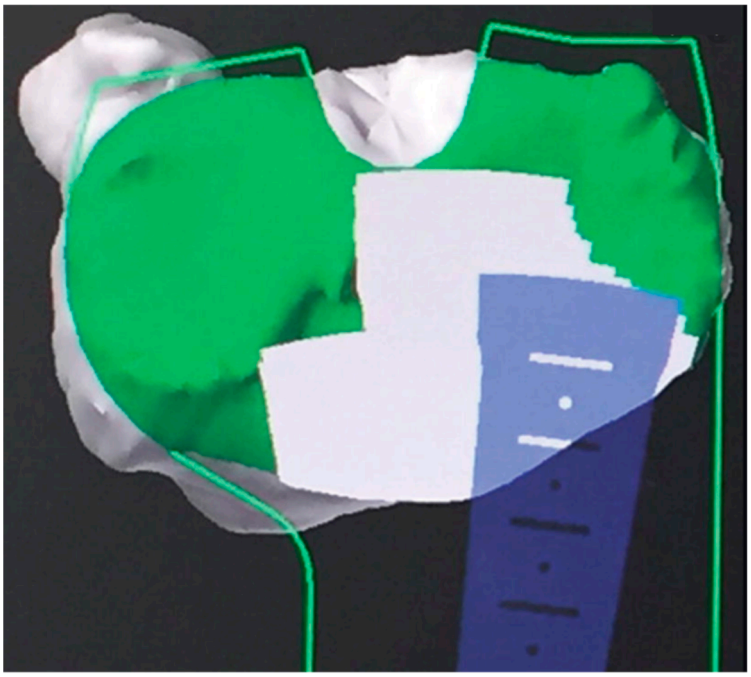

Figure 2. Example of tibial cut. Green area represents the amount of bone to be removed.

3.3. Outcomes and Cost-Effectiveness

MAKO® is the most studied system for robotic TKA (rTKA) in the literature, and published data show improvements in accuracy, precision, and soft tissue safety [9,17,19,22]. Other crucial points to analyze are the learning curve, the surgical time, and the fulfillment of patient expectations. Different cadaveric studies have demonstrated high precision [17,24], with slight differences between planned and performed bone cuts for the extension gap (0.1 mm), flexion gap (between −2 mm and 2 mm), and slope (1.1°) or component rotation (0.9°) [26–31], and there is less risk of soft tissue damage during bone cuts compared with cTKA [17,23]. These data are confirmed even in severe varus or valgus deformity [19,30,31]. The learning curve and surgical time are two crucial parameters to

consider in the analysis of rTKA cost-effectiveness. According to recent studies [32–34], rTKA requires slightly greater surgical time (from the incision to the suture) than the traditional TKA (82.5 vs. 78.3 min) for the first 20 cases performed through MAKO®, showing no significant difference in the mean surgical time of the second 20 cases (81.1 min vs. 78.3 min). Kayani et al. [32] described an improvement in the operative time when performing rTKA. There was no added operative time compared to cTKA after only seven cases, without any effects on accuracy and limb alignment [31,32]. In another study, comparing complex and non-complex rTKA, Stauss et al. [35] showed no statistical significance in surgery duration. According to the most recent data, patients who undergo TKA with MAKO® have a lower mean pain score at six months [36,37] compared to patients who underwent cTKA, with no differences at one year [38], showing better post-operative range of motion (ROM) at discharge [22] and 90 days after surgery. Moreover, rTKA patients demonstrated reduced early post-operative pain, decreased post-operative analgesia requirements, a good WOMAC score, and decreased length of hospitalization (mean 77 h vs. 105 h) [27,39–41] regardless of the complexity of the TKA (post-traumatic, obese patients, high-grade varus or valgus) [35]. Conversely, other studies demonstrated no statistically significant difference in post-operative Knee Society Score (KSS) and range of motion (ROM) at 30-, 60-, and 90-day follow-ups [33,36–39]. An increased complication rate due to increased operative time is a concern in rTKA. In particular, infections and blood loss are the complications most directly linked to surgical time. However, recent data (with a minimum follow up of 2 years) [42] show that the rate of early complications is not significantly different between MAKO® and conventional TKA [9,40]. Precisely, there is no evidence of a higher infection rate, blood loss [33,43], or revision after rTKA [9].

The main short-term complication described was manipulation under anesthesia (without a difference between robotic-assisted and cTKA [9]) and a minor wound dehiscence over the incision for the proximal tibial registration pins in the robotic TKA [41]. Regarding UKA, in a recent meta-analysis, Zhang et al. [44] confirmed the more precise implant positioning and lower complication rate as well as a lack of differences between KSS, WOMAC, infection, or re-intervention between rUKA and conventional UKA. The cost-effectiveness analysis must consider the system cost, the cost of the hospitalization, drugs (opioids) [34], complications, and surgical revisions. Varughese et al. [34] calculated that the price difference between rUKA and conventional TKA is 8353 USD vs. 13,342 USD, respectively, considering only the hospitalization and surgical expenses. At the same time, Cool et al. [45] and Cotter et al. [40] reported that patients undergoing rTKA using MAKO® had statistically significantly lower 90-day costs—up to 2090 USD lower compared with conventional TKA [9,40].

4. NAVIO

4.1. Principles

The NAVIO® surgical system (Smith & Nephew) is a semi-active, image-free, open-platform robotic assistant with a handheld robotic burr (manually controlled by the surgeon), approved in 2012 by the FDA for UKA and TKA [18] (Figure 3). It uses optical-based detectors and specific anatomical landmarks to create a 3D virtual knee model in the operative room, determining the implant's optimal bone resections, size, and positioning.

The system continuously controls the position of the patient's lower limb and the handheld burr, so that the limb position and the degree of knee flexion can be modified constantly during the surgical procedure to obtain the best exposure. As a semi-autonomous system, it checks the surgeon's movements to optimize accuracy and safety through speed control or tip retraction of the burr when the edge of the desired bone removal volume or a dangerous position is reached [19,43]. Compared to MAKO®, this robotic system does not require a pre-operative CT scan and a dedicated engineer. It is not possible to plan the TKA on a 3D model preoperatively, and it is a semi-active system.

Figure 3. NAVIO® surgical system. Reproduced with permission from Smith & Nephew.

4.2. Surgical Technique

4.2.1. Unicompartimental Knee Arthroplasty (UKA)

The surgical approach is the same as a conventional UKA. After the incision, careful debriding, and joint inspection, osteophytes can be removed from the medial, lateral, and intercondylar notch. The femoral and tibial trackers are placed through appropriate pins to allow the system to analyze the correct position and the optimal communication between the central machine and the trackers. At this point, the surgeon can place a checkpoint verification pin on the femur and tibia, and after the registration of essential anatomical landmarks (femoral pin, tibial pin, medial and lateral malleolus), dynamic parameters can be captured: first, the hip center is registered moving the knee circularly, then the knee kinematics with and without valgus (or varus, for lateral UKA) stress are captured in order to evaluate ligament tension and ROM, respectively. In the following step, the anatomical landmarks of the knee are recorded to obtain a 3D patient-based knee model. The next step, called "surface mapping," consists of digitalizing the tibial and femoral surface by moving the point probe over the entire articular surface. The absence of any radiological reference is both an advantage and a limit of this system. Although it limits patients' exposure to radiation, there is no implementation between radiological and intraoperative anatomy, obtaining the 3D model of the knee only by the captured landmarks. Once the 3D patient-specific model is obtained, the "planning" phase can start. The surgeon can manage the size and the positioning (antero-posterior and lateral view) of the components on the virtual bone surface. The system offers a 3D visualization of the components and the possibility to analyze the expected laxity of the soft tissues for the whole ROM (10° intervals), comparing the pre-and post-operative joint laxity. At this point, the bone cuts are performed through the handheld burr, correlating different colors on the virtual model to the bone in excess and to the depth. When trial components are positioned, the joint laxity throughout the ROM is tested again. If a cartesian diagram confirms the planned joint balancing, the definitive components can be implanted [43].

4.2.2. Total Knee Arthroplasty (TKA)

The first part of the operation is similar to UKA, particularly the removal of osteophytes, the placement of the trackers, and the checkpoint verification pins. Even in this case, after the registration of essential anatomical landmarks (femoral pin, tibial pin, medial

and lateral malleolus), the surgeon is asked to register the dynamic parameters of the hip center and the ROM. Different from UKA, these are captured with and without both valgus and varus stress in order to test the joint laxity. Even the anatomical femoral landmarks are partially different. In addition, the system registers the trans-epicondylar axis, the femoral AP axis, and the posterior condylar axis. The medial and lateral plateau point and the knee center, instead, are the tibial landmarks collected. Even the AP axis, the femoral mechanical axis, and the medial third of the tibial tubercle are registered. At this point, the procedure continues as for UKA, performing the surface mapping of both the tibial and femoral sides, planning the size and the prosthesis positioning, and comparing the expected results of gap balancing to the pre-operative laxity. The bone preparation is performed considering "Measured resection", since it is the only balancing technique allowed. There are two modalities to perform the bone cuts: the "all burr" modality, which consists of milling all the bone distal to the planned resection through the handheld robotic burr, and the "cut guides" modality, which uses the milling cutter to prepare the cylindrical fixation points to lock the guides and perform the bone cuts through a dedicated saw (Figure 4).

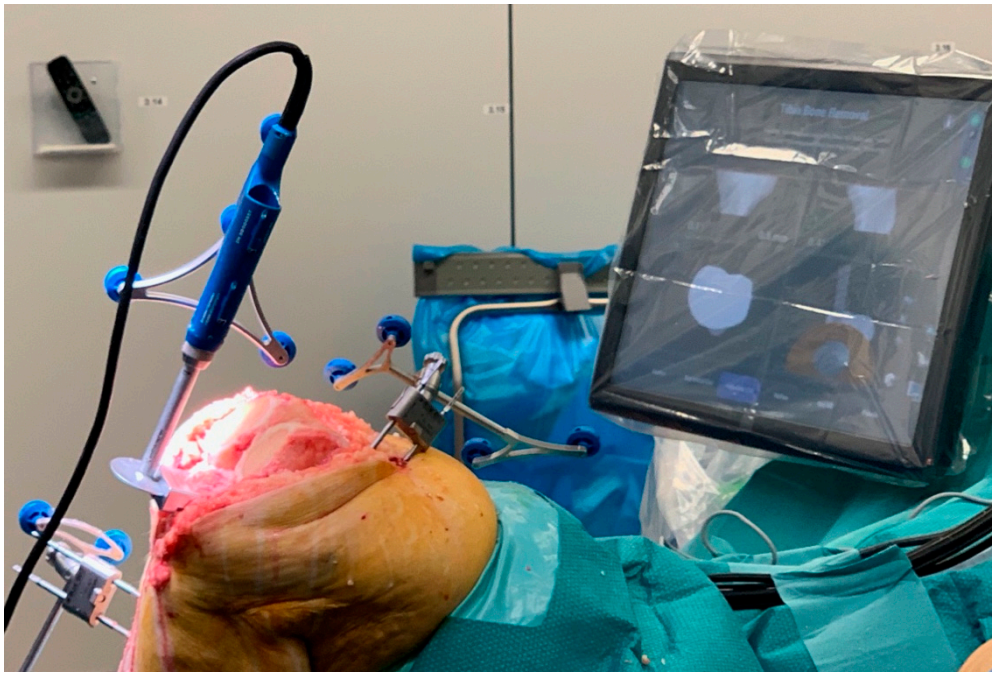

Figure 4. Intra-operative image showing the screen and the planning of the tibial cut in TKA.

Finally, after trial reduction, the joint laxity throughout the ROM is tested again, and if the planned joint's balancing is confirmed, the definitive components can be implanted [43].

4.3. Outcomes and Cost-Effectiveness

Four key points about the NAVIO® system should be evaluated to analyze the outcomes in the literature: (1) the learning curve, (2) surgical time, (3) accuracy, and (4) fulfilment of patient expectations.

Many authors demonstrated that after an initial learning curve with a long operation time, surgeons could expect a significant reduction in operative time after a small number of cases with this system [43,46,47]. In particular, the average surgical time for a surgeon approaching NAVIO® TKAs was reported as 68.2 min, compared to an average of 51.7 min for cTKA [43]. However, after 40 cases, the surgeon takes only 10 min longer than conventional TKA (18% more time), with no difference after 80 cases (less than 5% more time than conventional TKA) [43]. During conventional TKA, the components are aligned through intra- and extramedullary rods or measuring the resected bone through a manual caliper: this method can result in inaccurate placement, patient dissatisfaction, and

early failure [48]. NAVIO® accuracy, instead, was reported to be within 0.2–0.5°/0.5 mm in all three measured planes (coronal plane for varus/valgus angle, sagittal plane for femoral flexion angle, and depth of femoral resection), with a minimum difference between the pre-operative plan and post-operative radiographic measurements. Only 8.5% of the rTKAs performed with this robotic system go beyond the acceptable accuracy threshold of +/−3°, demonstrating high accuracy and reproducibility for TKA [43,46]. Soft-tissue laxity, instead, has an average deviation from the predicted plan between 0 and 90° of 0.9 mm in both the medial and lateral compartments, and it decreases up to 1.0 mm in the mid-flexion arc [43]. Even UKA shows significantly higher levels of accuracy with NAVIO compared to conventional UKA [46], with a significantly lower rate of post-operative limb malalignment (26 vs. 61%; $p = 0.018$) [43]. The primary determinant of patient satisfaction is the fulfillment of patient expectations, such as pain relief and improved knee function [49]. Recent studies demonstrate that RAS performed with NAVIO® showed a faster return to sport (4.2 vs. 10.5 months) [9], improved functional ability, and reduced pain levels, with 100% of patients returning to sport [43] compared to traditional surgery. Finally, the NAVIO® system is correlated with a lower complication (but not significative) rate and an early discharge [50]. Improving patient satisfaction is not only crucial for the quality of care, but it is also essential for health costs [51]. In particular, robotic-assisted UKA costs are stackable to traditional UKA over five years and become cost-saving beyond seven years, considering early complications and revision [52].

5. ROSA

5.1. Principles

The ROSA Knee System® is the most recent robotic system. It was approved by the FDA in January 2019 [53] (Figure 5). It is a semi-active system developed only for TKA, in particular for Persona® (Zimmer Inc., Warsaw, IN, USA), Vanguard® (Zimmer Inc., Warsaw, IN, USA) and NexGen implants® (Zimmer Inc., Warsaw, IN, USA) [54]. A robotic arm holds and places the cutting guides while the surgeon controls the saw through the jigs. This robotic system is different compared to the other systems available on the market because of two principal features: it does not have a milling cutter for bone resections (i.e., NAVIO®), and it offers a computer software program to convert two-dimensional knee radiographs into a three-dimensional patient-specific bone model (X-Atlas technology, Zimmer Inc., Warsaw, IN), allowing for a pre-operative plan without the necessity of a CT scan [8,55] (there is even the possibility to plan the TKA on a CT scan). According to recent studies, this new technology is highly precise and accurate, predicting the implant size in 93.1% of the cases (higher than classical 2D planning) [56]. These principles of the ROSA Knee System® are thought to carefully preserve the natural surgical flow and minimize extra time related to robotic surgery [53]. Particularly, by using a standard saw (not included or assembled in the robotic system) manually guided by the surgeon, the system avoids the increase in surgical time when setting the saw on the robotic arm, and it reduces complications due to calibration errors [53].

5.2. Surgical Technique for TKA

Once the robotic system and the patient are correctly positioned, draped, and prepared, a standard TKA surgical approach is performed according to the surgeon's preferences. An optical tracker is positioned both on the femur and tibia, 10 cm above and under the incision, so that the surgeon is ready to register the femoral and tibial anatomic landmarks through different specific instruments.

In particular, for the femur, the head center is the first parameter captured through circular movements of the hip, followed by the femoral canal entry, the posterior condyles, the anterior and posterior trochlear groove, the medial and lateral epicondyle, the medial and lateral distal condyle, and finally the anterior cortex. The registered parameters for the tibia, instead, are the malleoli, the tibial tubercle, the tibial canal entry, the PCL insertion

point, and the medial and lateral plateau resection reference. Figure 6 shows the pins and the checkpoint evaluation.

Figure 5. ROSA Knee System®. Reproduced with permission from Zimmer Inc.

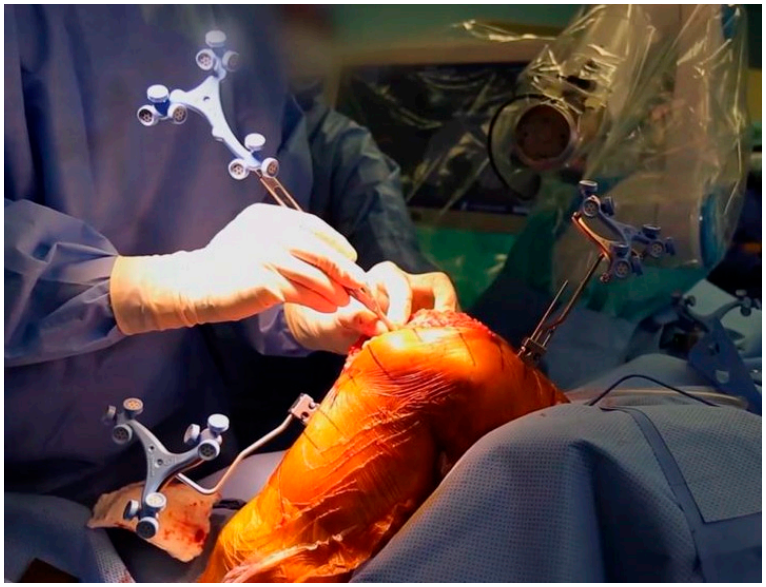

Figure 6. Intra-operative checkpoint evaluation with ROSA Knee System®.

At this point, a dynamic knee evaluation is performed: the surgeon can move the knee through a series of optically tracked movements of the leg to evaluate the ROM and laxity of the knee. The system will quantify, display, and save different features, including ROM, alignment, and joint laxity [55,56]. In particular, there are two options to measure knee laxity: providing both varus and valgus stress while flexing the knee through the full ROM or evaluating the varus and valgus stress at a pre-set angle (by default, 0° and 90°, but it may even be 30–45–60° and 120° according to the surgeon's preferences). This laxity

assessment can be performed at three stages of the surgery: the initial, intraoperative, and final stage. The ROSA Knee System® allows the surgeon to choose between three different workflows (before creating a 3D plan). These are: "measured resection," "gap balancing," and "hybrid" [57,58]. After this phase, a 3D model of the knee can be created based on anatomical findings alone or on the fusion between anatomical findings and radiographs. The system shows some differences between the image-based and imageless plans: the type and size of the tibial component cannot be selected in the imageless cases, and the 3D bone model is shown only for image-based cases. Moreover, the imageless panel does not offer the axial view nor the option buttons for showing the implants, cuts, axis (always shown in flexion), and landmarks. The surgeon can now plan the entire surgery, including bone cuts and implant positioning (Figure 7) [57,58].

Figure 7. Intra-operative phase with summary of implant positioning, amount of resection, and alignment evaluation.

Once the surgical planning is acceptable and the cutting guide is assembled on the robotic arm, the system places the jig in the correct position, and the surgeon, after checking the position of the guide, can perform the bone resection manually. When the bone cuts are completed and the trial components are positioned, the surgeon can test the ROM and soft tissue balancing. If the planned joint balancing is confirmed, the definitive prosthesis can be implanted [54,57,58].

5.3. Outcomes and Cost-Effectiveness

Due to the recent approval by the FDA, there are still few studies on TKA performed through the ROSA Knee System®. Regarding the accuracy, in a cadaveric study, Parratte et al. [53] performed 30 TKAs using the same ROSA workflow (measured resection) based on imageless planning and implanting three different prosthesis models (Persona®, NexGen®, and Vanguard®, Zimmer Inc., Warsaw, IN, USA). According to their measurements, the mean differences between the planned angles and the measured values were close to 0° (SD > 1°). Even Seidenstein et al. [59], in another cadaveric study, compared 20 conventional TKAs to 14 rTKAs, showing statistically more accurate results ($p < 0.05$) and fewer alignment outliers (±3°, $p < 0.05$) for rTKA. Particularly, comparing the planned angles and resected bone on the cadaveric knees, for the rTKAs, the accuracy of all bone resection angles was below 0.6°, with SDs below 0.4°. Moreover, the final limb alignment of the robotic group had an accuracy and SD below 1°. All values of the robotic group had a higher percentage of cases, within 2° and 3° of the target, and 100% of cases were within 3°. Shin et al. [60] instead described a high accuracy (89–100%) for the coronal angles but a lower precision in the sagittal plane (74–77% accuracy).

According to recent studies [61,62], the ROSA Knee System® has a short learning curve of 8.7–9 cases, with no influence on the accuracy (higher precision than conventional TKA, outliers ±3° 5.2% vs. 24.1%, respectively) [62], no significant operative time difference between rTKA and conventional TKA (107 ± 16 vs. 111 ± 22 min, respectively), and no complication rate differences. Unfortunately, no "in vivo" studies compare ROSA Knee System® outcomes with those of other preexistent robotic systems. A comparison of the outcomes among these three systems is reported in Table 2.

Table 2. Summary of outcomes and scores of the three robotic systems: MAKO® [9,63]; NAVIO® [64–67]; ROSA® [68,69].

	MAKO® (Stryker Ltd., Kalamazoo, MI, USA)	**NAVIO® (Smith & Nephew, Andover, TX, USA)**	**ROSA® (Zimmer Inc., Warsaw, IN, USA)**
ROM	119° at 1 year PO	130.3° at 1 year P.O.	135.8 ± 10.2 at 1 year P.O.
satisfaction	94% (vs. 82% cTKA) at 1 year P.O.	81.8–82% at 1 year P.O. ARE	95% vs. 92.5% (cTKA) at 1 year P.O.
womac	WOMAC score: 6 ± 6 vs. 9 ± 8 (cTKA, $p < 0.05$)	87.05 ± 7.74 vs. 81.76 ± 8.95 cTKA ($p < 0.0001$) ADAMSKA CORI	N/A
KSS	F-KSS:80 (vs. 73 cTKA) at 1 year P.O.	F-KSS: 92.8–99.9 at 1 year P.O.	F-KSS 84.6 ± 15 vs. 79.1 ± 19 at 1 year P.O.
	K-KSS:85 (vs. 82 cTKA)at 1 year P.O.	K-KSS: 91.9–96.9 at 1 year P.O.	K-KSS 92.3 ± 10 vs. 93.2 ± 6 at 1 year P.O.
post operative vas pain score	VAS 2.6 (vs. 3.5–4.5 cTKA) at 6 weeks P.O.	VAS 2.5 ± 1.2 1 year P.O. TURAN	VAS 1 vs. 2 (cTKA) at 6 months
complications	no difference rTKA vs. cTKA	no difference rTKA vs. cTKA ARE	no difference rTKA vs. cTKA

6. Other Robotic Systems

6.1. OMNIbotics® System

The OMNIBotics® platform is an imageless, passive robotic system that has been available since 2007. It allows for the possibility to perform TKA through kinematic or mechanical alignment [69]. The OMNIBotics® system includes three components: the BoneMorphing 3D statistical shape modeling, the OMNIbot® robotic cutting guide, and the recently developed BalanceBot® ligament balancing tool [69]. The surgical planning is similar to the other robotic systems previously described, with two optical trackers (femoral and tibial) to create a 3D virtual model of the knee through the digitalization of anatomic landmarks (hip center, malleoli, ankle center, center of the distal femur, and proximal tibia) and to determine the implant's optimal bone resections, size, and positioning. The most innovative component of this system is BalanceBot®: a miniature ligament-balancing robotic device that can help the surgeon with the gap planning. After the planning phase, the OMNIbot® cutting guide assists the surgeon in performing the bone cuts. The OMNIBot® is a miniature robotic guide set on the medial side of the distal femur, which moves automatically around the distal femur, stopping at each resection plane to allow the surgeon to make the bone cuts. The tibial cut, instead, is planned in the same three-dimensional virtual environment, but the delivery is via a quick attachment, multi-planar adjustable pinned single-slot cutting guide. After testing the trial components, the final TKA will be implanted [70]. Although published outcomes are limited, the most recent literature demonstrates good short-term PROMs and survivorship data that compare favorably to other robotic systems [69]. Moreover, the OMNIbotics® system shows a high level of precision in surgical planning, with improved accuracy compared to conventional and navigation technology (37% of the femoral cuts are within a half degree of the planned

cut angle, 63% of axial rotations are within a half degree, and 50% of the tibia slope cuts are within a half degree of the planned value) [69].

6.2. CORI System

The CORI® system (Smith & Nephew) is a semi-active, image-free, open-platform robotic assistant with a handheld robotic burr (manually controlled by the surgeon) that has been used since 2020. It is considered the evolution of NAVIO® [71]. Due to its recent approval, no work has compared this system to other robotics systems, but it seems to be faster in resections, with an improved workflow. Some papers consider CORI® and NAVIO® as the same robotic system, with improvements in outcomes and survivorship compared to cTKA, but in 57% of the studies, there is a conflict of interest or factory funding [72].

7. State of the Art and Future Perspectives

RAS definitely has different advantages, such as decreased radiation exposure for rTKA in an imageless robotic system, increased accuracy, early discharge, and thereby reduced costs of healthcare (after initial costs) [9,38,53], especially in high-volume centers (more than 50 cases per year) [73–75]. On the other hand, according to the most recent literature, there are no differences in outcomes comparing the three systems (except for less blood loss for MAKO®) [64,72]. In a recent study on the cost-effectiveness of rTKA, through a two-ways deterministic analysis, Rajan et al. [76] calculated that RAS is economically convenient if the revision rate is less than 1.6%, and when the cases performed every year are more than 42 or 24 in number according to the richness of the population, defined as the maximum cost a population is willing to pay for additional "Quality-adjusted life year" (deadline of 50,000 USD or 100,000 USD). A low revision rate was demonstrated for rTKA compared to conventional TKA both for early (>1 year) and late (>1 year) revision (0.78% and 1.5%, respectively, for rTKA and 0.3% and 0.6% for manual TKA). This different revision rate influences healthcare costs by increasing the "Quality-adjusted life year" of the patients and the expenses for a second surgery [76].

Despite these advantages, RAS has yet to gain acceptance among orthopedic surgeons and expand its field of application [45]. One of the reasons for this could be that according to a recent systematic review by DeFrance et al. [77], up to 91% of the studies comparing conventional knee arthroplasty and rTKA/rUKA included a conflict of interest or were industry-funded: 87% of these studies favor robotic arm assistance, and 13% report equivocal results. Moreover, the barriers to the acceptance of surgical navigation are related to operative glitches, difficulty with intra-operative registration, the initial increase in surgical time according to the learning curve, and finally to the initial significant economic investment for buying the robotic system [40,43,45]. However, different improvements in RAS technology must be accomplished, and the companies are evaluating different solutions and future perspectives. One of the most debated topics in RAS development concerns radiological imaging support. Some authors have considered the fusion between MRI (instead of CT scan) and intraoperative images, which could highlight critical structures such as nerve roots or vascular structures [78], expanding the application of RAS in other surgeries (i.e., spine surgery) in which it can be more suitable to the surgeon's necessities, using a CT scan, MRI, or imageless-based planning according to the surgical operation [18,78,79]. Another essential future improvement for RAS might be the development of a network of surgical and anatomical models based on the acquisition and elaboration of anatomy and biomechanical data, in order to prevent surgical errors and improve accuracy [79]. The introduction of robotics for knee osteotomies, anterior cruciate ligament reconstruction (ACLR), and bone reconstruction in oncologic orthopedics could represent a turning point in knee surgery [80]. Notably, Lo et al. [81] stated that despite being more technically demanding, time-consuming (because of bone landmark registration), and expensive, arthroscopy-assisted computer navigation is safe, accurate, and reliable for high tibial osteotomy (HTO), since the mean deviation between post-operative coronal

plane alignment and intraoperative computer images is about 1° (range: 0.1–1.9°). Even the mean intersection of the mechanical axis over the tibial plateau shows high accuracy, with a mean deviation of 3% (range: 0–7%) from the intra-operative images. The same results were shown by Saragaglia et al. [82], confirming high accuracy for HTO, double-level osteotomy (DLO) for genu varum, distal femur osteotomy (DFO), and the measurement of the mechanical medial proximal tibial angle (mMPTA). In this work, the pre-operative goal (HKA angle: 184° ± 2°) was reached in 96% of cases of HTO, and the difference was statistically significant compared to the non-navigated series (71%). Regarding DLO for genu varum, the pre-operative goal was reached in 92.7% of cases for the hip-knee-ankle (HKA) angle and in 88.1% of cases for the mMPTA. In the DFO, the pre-operative goal was achieved in 86.2% of cases for the HKA angle and in 100% of cases for the mMPTA [82]. Finally, CAS helps the surgeon to better preserve the native posterior tibial slope (PTS), especially in closed-wedge HTO [83]. Regarding ACLR, the literature agrees on using robotic systems (CAS) for technical assistance in tunnel positioning, improving the knowledge of the kinematic behavior of ACL, studying knee laxity, and improving the outcomes of ACL reconstruction [84]. The literature is controversial [85], and though proponents of CAS argue that it can improve the positioning of tunnels in order to avoid graft failure [85], some authors reported no statistically significant differences between tunnel placement performed with robotic systems or by experienced surgeons [86]. For these reasons, over the years, robotics in ACL reconstruction has been increasingly used to study knee kinematics [85,87] rather than for tunnel planning and positioning. Moreover, Margier et al. [88] demonstrated that CAS is not cost-efficient in ACL reconstruction, leading to higher operating time, higher expenses, additional incisions, and no significative outcome differences for patients [85,89].

A recent innovation in the world of sports medicine consists of the use of robotics for osteochondral knee lesions. Through different studies on cadavers [90,91], this has shown an increase in accuracy and precision in both the harvest and placement of the graft [92]. In this field, Zaleski et al. [93] applied CAS to plan an osteochondral allograft reconstruction for a post-traumatic tibial plateau defect, with precise pre-operative planning and the creation of patient-specific osteotomy guides (PSI). The operation was performed with lower operative times than conventional techniques and with higher precision of the allograft size and positioning.

Finally, robotic surgery could be increasingly involved in orthopedic oncology due to the complexity of bone resections and subsequent reconstructions [94].

8. Conclusions

The introduction of RAS technology has different advantages and some disadvantages. Improved accuracy of bone cuts and implant positioning are some advantages related to RAS. However, the challenge is to prove that the high accuracy and precision obtained with rTKA can be translated into improved patient-reported outcomes and long-term survivorship. Recent studies have demonstrated that robotic technology provides higher accuracy and reliability when performing TKAs, reproducing the pre-operative plan on the patient limb alignment with minimal deviation and offering a short learning curve as well as equivalent operative times to conventional jig-based TKA. However, rTKA still has some limitations, including the initial economic investment, additional radiation exposure for the patients (due to pre-operative CT scans with image-based platforms), and increased operative times during the first part of the learning curve [49]. In the future, robotics may become a valuable resource to help the surgeon in patient-specific TKA, ligament reconstruction, and sports medicine, offering high accuracy, precision, and good outcomes.

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