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Robotic-Assisted Unicompartmental Knee Arthroplasty: State-of-the Art and Review of the Literature

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ABSTRACT

Background: Unicompartmental knee arthroplasty is a successful treatment for unicompartmental knee osteoarthritis that has lower complication rates, faster recovery, and a more natural feeling knee compared to total knee arthroplasty. However, long-term survival has been a persistent concern. As more surgeon-controlled variables have been linked to survival, interest in robotic-assisted surgery has continued to grow.

Methods: A review and synthesis of the literature on the subject of robotic-assisted unicompartmental knee arthroplasty was performed.

Results: We present the driving factors behind the development of robotic-assisted techniques in unicompartmental knee arthroplasty and the current state-of-the art. The ability of surgeons to achieve intraoperative targets with robotic assistance and the outcomes of robotic-assisted surgery are also described.

Conclusion: Robotic-assisted surgery has become increasingly popular in unicompartmental knee arthroplasty, as it allows surgeons to more accurately and reproducibly plan and achieve operative targets during surgery. Cost remains a concern, and it remains to be seen whether robotic-assisted surgery will improve long-term survivorship after unicompartmental knee arthroplasty.

Unicompartmental knee arthroplasty (UKA) is a successful surgical option for patients with end-stage, unicompartmental osteoarthritis. Major advantages of UKA compared to total knee arthroplasty (TKA) include quicker recovery and a lower overall complication rate [1]. Patients undergoing UKA can expect a 96% chance of return to their preoperative activity level, and 90% maintain or experience improvement in their sporting activities [2,3]. This is in contrast to TKA, where dissatisfaction rates hover around 14%-19% [4,5]. However, the durability of UKA has been inconsistent, and aside from proper patient selection, the execution of surgical goals in the operating room is the critical factor for function and longevity in UKA [6]. Given the technically challenging nature of performing UKA through a minimally invasive approach, the interest in robotic-assisted surgery has increased [7–10]. This article will review the historical performance of conventional UKA, the technical parameters required for achieving a durable UKA, the rationale for robotic UKA, the currently available commercial systems, and the performance of robotic-assisted UKA to date.

Durability and Survivorship of Conventional UKA

Despite excellent functional outcomes achieved for the majority of patients, long-term survival has been the most pressing issue concerning the viability of conventional UKA. In both longitudinal studies and registries, survivorship of UKA has lagged behind TKA (Fig. 1).

Looking at the Australian and Swedish registries, the revision rates for UKA at 2 years were 4.8% and 4.5%, respectively [12]. As time went on, younger patients fared worse, and cumulative revision rates increased as the patients decreased in age. For patients under 55, cumulative revision rates at 7 years was 19%, compared to

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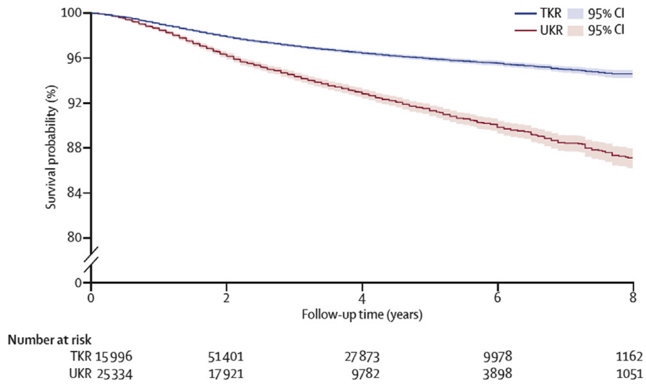

Fig. 1. Kaplan-Meier curve demonstrating comparative revision rates of UKA vs TKA to 8 years in matched patients.
Permission kindly given by Liddle et al [11].

5.7% for patients over the age of 75. The main reason for revision of UKA in osteoarthritis patients less than 65 was loosening/lysis in both cohorts, making up 54% of revisions in the Australian registry and 39% of revisions in the Swedish registry. In general, younger patients had a higher risk of revision, and surgical technique likely played a role in many of these early failures.

These data are echoed in the Finnish Arthroplasty Register as well, where UKAs were found to have 73% survival at 10 years [13]. A separate paper examining the Finnish registry found that survivorship of UKA was 89.4% at 5 years and 80.6% at 10 years, compared to 96.3% at 5 years and 93.3% at 10 years for TKA [14]. These differences were significant after adjusting for the age and gender of the patients, as well. Slightly better results were reported by Bordini et al [15], who found 86.8% survivorship at 10 years in the Register of Prosthetic Orthopedic Implants out of northern Italy, with 42% of the cases failing due to aseptic loosening. However, this is still inferior to modern TKA survivorship at 10 years, and suggests that surgical technique plays an important role in the overall success of UKA. A multicenter retrospective study by the French Society for Hip and Knee evaluated 418 failed UKAs, 19% of which failed in the first year and 48.5% failed within the first 5 years [16]. Loosening was the main reason for failure in 45%, and the authors concluded that this finding suggests a major role for surgical technical issues in UKA. The majority of this loosening was due to early fixation failure, likely due to malpositioning of the implants, leading to mechanical overload of the limited fixation surface.

Interestingly, these survivorship trends are reversed in smaller longitudinal studies from high-volume centers. A randomized, controlled trial between UKA and TKA for patients with unicompartmental arthritis demonstrated better functional outcomes and survivorship for the UKA patients [17], and a comparative study found that onlay medial UKA had no difference in mid-term results compared to TKA [18]. Investigators at the Mayo Clinic found no difference in survivorship in UKA vs TKA in patients >75 years old [19]. Argenson et al [20] demonstrated excellent survivorship of 94% at 10 years and 74% at 20 years with cemented, metal-backed prostheses. A 5-surgeon, multicenter cohort from the United States demonstrated 90% survivorship at 10 years [21], and a single surgeon, retrospective study looking at 173 medial UKAs from the United States reported 95% implant survivorship at 10 years, as well [22]. Even in the more challenging lateral compartment UKAs, similar results are reported. Lustig et al [23] reported 94.4% and 91.5% survival at 10 and 15 years, respectively, in 54 lateral UKAs. These results suggest that, despite registry data demonstrating inferior survivorship of UKA to TKA, comparable outcomes can be achieved by experienced, high-volume surgeons. However, for the less specialized surgeon, conventional UKA may impart significant revision risk to the patient.

Table 1
Variables That Influence Outcome of UKA (Controlled by Robot vs Independent).

Variables Controlled by Robotic Tool	Variables Independent of Robotic Tool
Implant positioning	Patient selection
Soft tissue balance	Soft tissue handling
Lower limb alignment	Implant design
Proper sizing	Fixation

Surgical Variables That Influence the Outcome of UKA

UKA outcomes are highly correlated to surgical volume. This has been described in multiple registry studies, and holds true for both surgeons and hospitals. Robertsson et al [24] initially looked at UKAs performed from 1986 to 1995 in the Swedish registry, and found that orthopedic units that performed less UKAs had increased rates of revision, especially in more technically challenging implant designs. Interestingly, the most commonly used design in that country was the least affected by experience, and as expected, a design with a poor track record had high revision rates despite the experience of those implanting it. Badawy et al [25] found significantly improved revision rates with the Oxford UKA as hospital volume increased in the Norwegian Arthroplasty Register, and the same authors found similar data looking at the Nordic Arthroplasty Register Association database from 2000 to 2012 [26]. The National Joint Registry for England and Wales demonstrates similar trends when it comes to surgeon volume, as well. Liddle found that surgeons performing fewer than 10 UKAs per year had an 8-year survival rate of 87.9%, while surgeons performing 30 or more UKAs had a 92.4% survival rate at 8 years. Interestingly, high-volume UKA surgeons had survival rates similar to that seen after TKA [27].

A number of surgical parameters have been identified that influence the outcome of UKA (Table 1). Overall limb alignment, implant positioning in multiple planes, implant sizing, ligament balancing, and maintenance of the joint line have all been shown to play a role in function and survivorship after UKA. In general, limb alignment should be corrected toward neutral, but slight undercorrection of the initial deformity may result in the best outcomes. Hernigou and Deschamps [28] studied polyethylene wear and lateral compartment degeneration after medial UKA, and found that severe undercorrection of the varus deformity leads to increased wear, and overcorrection into valgus leads to more rapid degeneration in the lateral compartment. In another study, slight varus alignment was found to result in optimal International Knee Society knee scores after medial UKA [29], a finding which was confirmed in a more recent study by investigators at our institution [30]. Lateral UKAs perform best when the valgus deformity is undercorrected, and when left in slight valgus alignment can achieve the functional outcomes similar to medial UKA [31,32].

Implant positioning in multiple planes has been shown to affect survivorship and outcomes as well, especially on the tibial side. Collier et al [33] looked at 245 fixed-bearing UKAs and found that leaving the medial tibial plateau with varus angulation and failure to reduce the varus hip-knee-angle resulted in higher failure rates. Using radiostereometric analysis, Barbadoro et al [34] found that varus angulation of the tibial component >5° resulted in increased implant micromotion that could lead to loosening. Hernigou and Deschamps [35] retrospectively reviewed 99 UKAs with average follow-up of 16 years and found that posterior tibial slope >7° was associated with a higher risk of loosening, especially in anterior

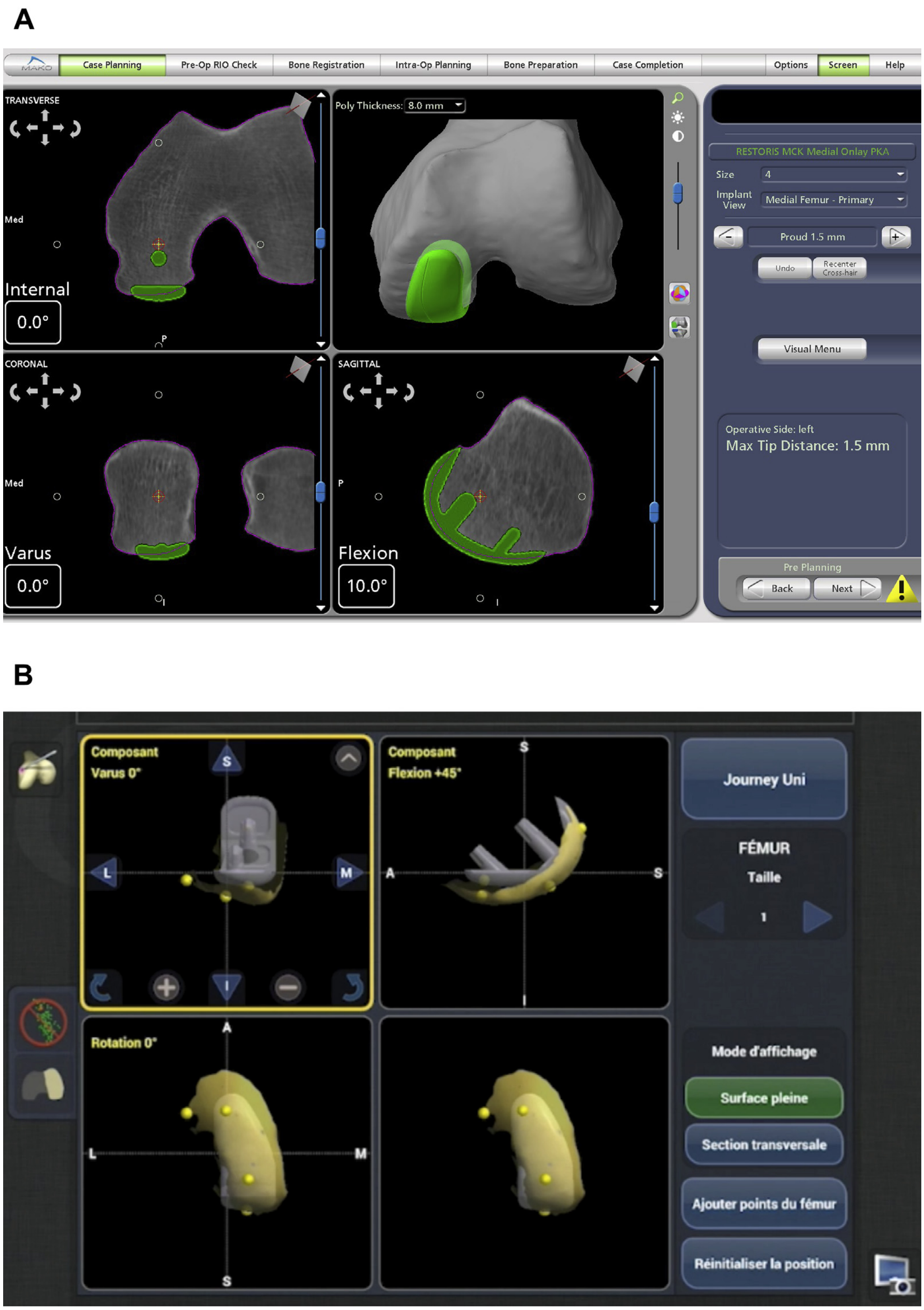

Fig. 2. Preoperative planning of component positioning in (A) image-based and (B) image-less systems.

cruciate ligament-deficient knees. Sizing of the tibial component appears to matter, as well. Tibial components with >3 mm of overhang were found to have significantly worse Oxford Knee Scores at 5 years after surgery, but there was no difference between implants with <3 mm overhang vs components that were undersized [36]. However, the authors still cautioned against significant undersizing because of the risk of subsidence and loosening. On the femoral side, the same group looked at femoral component position of the Oxford UKA as it relates to functional outcomes and radiolucency around the implants, and found no difference within the range of 10° of varus/valgus angulation or 10° of flexion/extension [37]. The authors concluded that the spherical design of the Oxford UKA femoral component made it clinically tolerant to significant malalignment.

Restoration of the joint line in both the medial and lateral compartments appears to play a role in successful outcomes following UKA, as well. Finite element analysis has demonstrated increased contact stress on both the polyethylene insert and articular cartilage when the joint line was elevated 6 mm [38], and

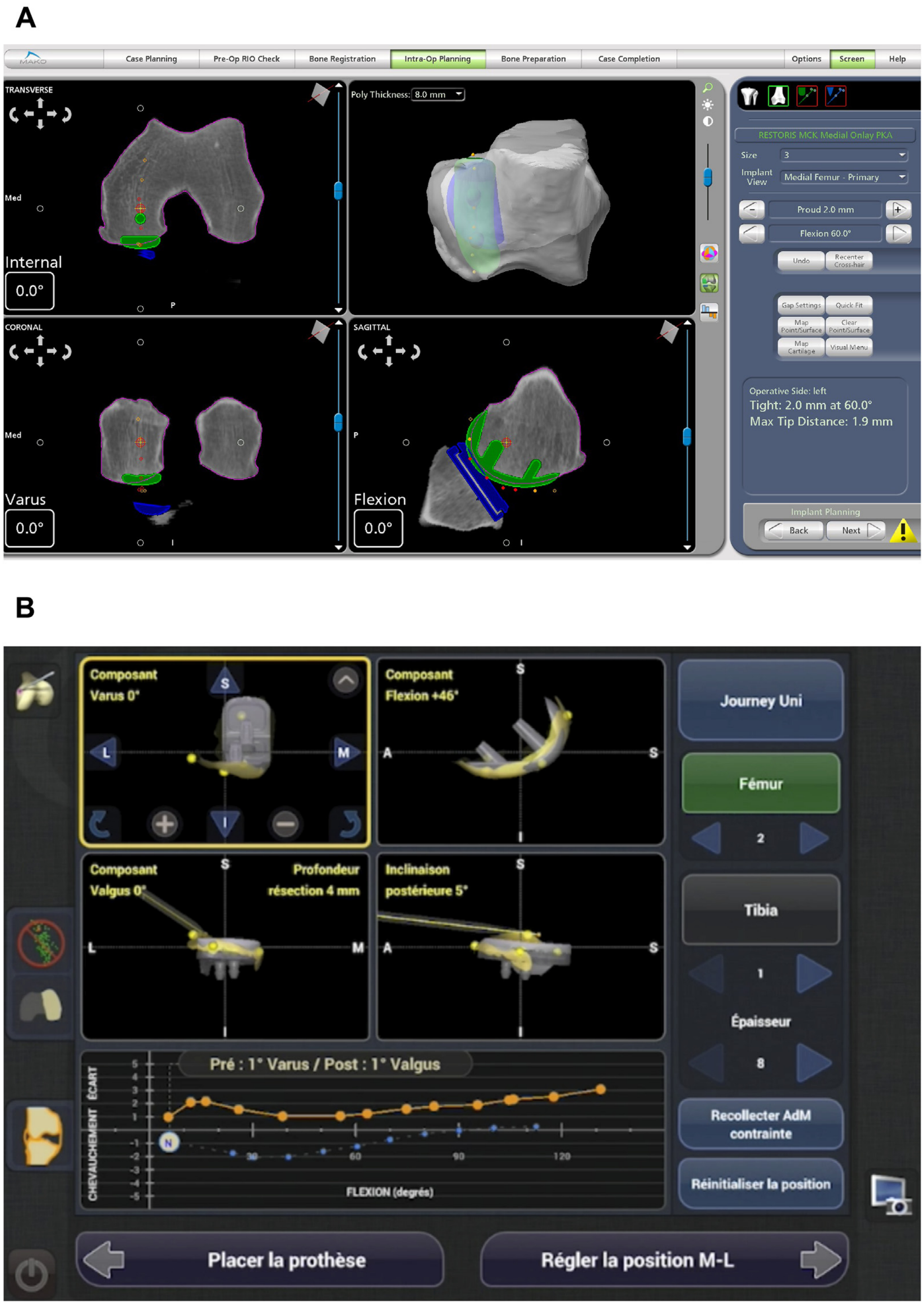

Fig. 3. Ligament balancing in (A) image-based and (B) image-less systems.

alignment correction has been tied to joint line placement [39]. Using a validated software model for measuring joint congruence, Khamaisy et al [40] demonstrated that well-conducted medial UKA improves the congruence and joint space width of the lateral compartment. The same group demonstrated similar results using the same algorithm to look at lateral UKA, as well [41]. Interestingly, a separate study showed that when the medial joint space is >2 mm or >40% thickness of the lateral joint space preoperatively, the reoperation rate after medial UKA was 6 times higher, indicating again that appropriate attention be paid to the joint line in both compartments [42]. Elevating the medial joint line more than 5 mm has also been shown to result in loss of extension after UKA [43]. However, with conventional instrumentation, this decision is largely made by surgeon feel, making it a potential source of intraoperative error that will affect the patient's outcome.

Rationale for Robotics in UKA

Given the sensitivity of UKA survivorship and functional outcomes to small changes in component position, robotic-assisted

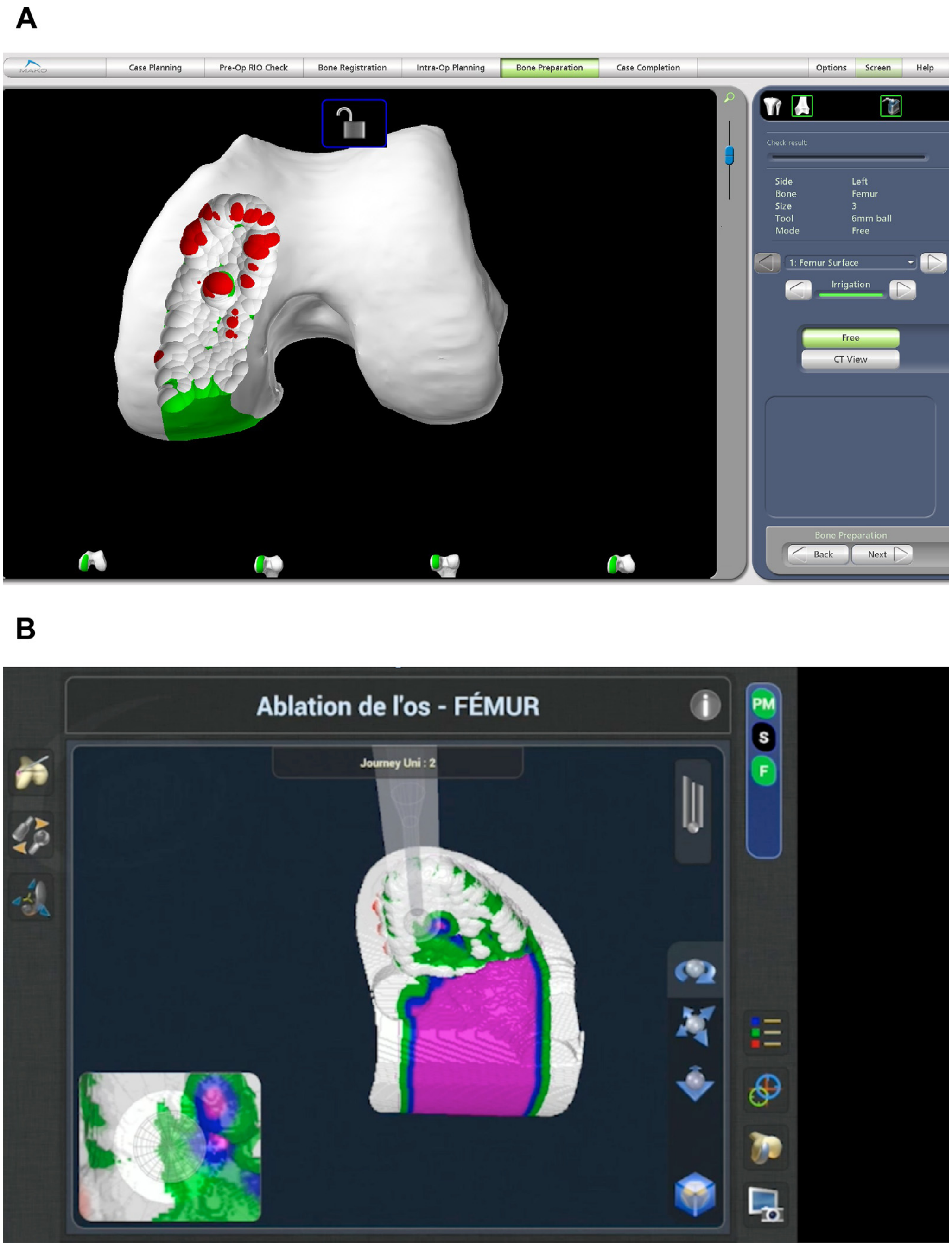

Fig. 4. Bone preparation in (A) image-based and (B) image-less systems.

surgery has become an attractive method for ensuring accurate execution of the surgical plan. In 2006, 2 studies were published that demonstrated the ability of robotic techniques to improve accuracy in UKA. Keene [44] compared 20 navigated and 20 conventional UKAs, and demonstrated that the navigated group was implanted within 2° of the preoperative plan 87% of the time vs 60% of the time in the conventional group. Cobb et al [45] performed a randomized, controlled trial, and showed that while the robot achieved coronal plane alignment within 2° of the computed tomography (CT) plan 100% of the time, conventional methods succeeded in that goal only 40% of the time. These early studies highlighted the ability of robotic assistance to reliably position implants appropriately, leading to more widespread use of robotic technology.

Robotic UKA Systems

Two systems are Food and Drug Administration approved and commercially available in the United States for UKA. In Europe, the Acrobot surgical system, which is an image-based semiactive robotic system, has been used for UKA surgery [45]. All systems currently available are closed, meaning that they can only be used with a single implant company. To date, there have been no studies to the authors' knowledge comparing the accuracy or outcomes of one system vs the other.

The Stryker/Mako haptic guided robot was introduced in 2005, and has 20% market share for UKA in the United States [46]. This system requires a preoperative CT scan from which subsequent planning is performed. Implant size and position are

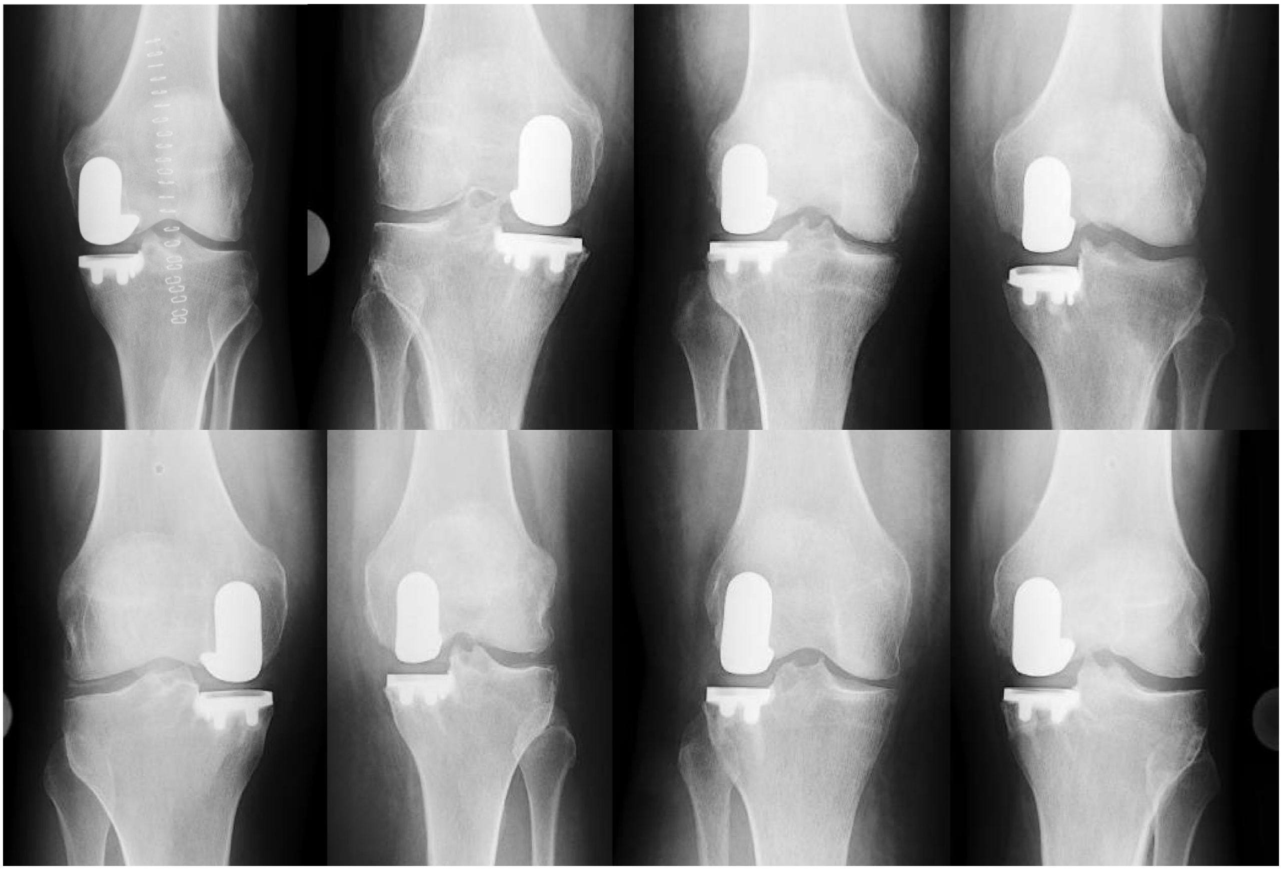

Fig. 5. Final X-rays of 8 consecutive robotically assisted unicompartmental knee arthroplasties.

carefully templated (Fig. 2A). Intraoperatively, image arrays are rigidly fixed to the tibia and femur with pins, and the surface geometries of the distal tibia and proximal femur are mapped and matched to the CT-based plan. A burr is employed by the robotic arm to remove bone, which is under direct surgeon control and gives tactile feedback (Fig. 4A). The resection area the burr is allowed to operate in is physically confined to the preoperative template by the robotic arm. During the operation, the system provides the surgeon information on limb alignment and soft tissue balance, which the surgeon may use to alter the position of the components (Fig. 3A). After implantation of the final components, information on alignment and ligament balance is used to select the appropriate polyethylene insert.

The other system available in the United States is the Navio Precision Free-Hand Sculptor made by Blue Belt Technologies, which is now available through Smith & Nephew. This is an imageless system that uses a hand-held device rather than a robotic arm, but maintains many of the same features as the Mako system. Reference arrays are rigidly fixed to the tibia and femur with pins. Registration of the surfaces of the distal femur and proximal tibia is performed using an image array wand, creating a three-dimensional reconstruction of the bony surfaces. Implant positioning and ligament balancing is then determined prior to bony resection (Figs. 2B and 3B). Resection is then performed using the hand piece burr that is optically tracked by the system so that it will not remove bone outside of the predetermined plan (Fig. 4B). After implantation of the final components, alignment and balance data are obtained again to determine the final polyethylene insert size.

Control of Surgical Variables With the Robot

The ability of robotic-assisted systems to control surgical variables affecting outcomes in UKA has been well documented. Regarding tibial implant positioning, Lonner et al compared postoperative radiographs to preoperatively planned implant position in 31 patients who underwent robotic arm-assisted UKA vs 27 patients who underwent UKA using conventional instrumentation. Robotic assistance reduced both the root mean square error and the variance in tibial component positioning in the coronal and sagittal planes [47]. Looking at both components, Citak et al performed a cadaver study where they performed conventional UKA on the left knee and robotic UKA on the right knee. They found that robotic-assisted UKA made femoral component placement 3 times more accurate and 3.1 times less variable than conventional methods, and made tibial component placement 3.4 times more accurate and 2.6 times less variable [48]. Similar results were found in a randomized, controlled trial of 120 patients, of which 62 had undergone robotic-assisted UKA. The authors observed that the accuracy of component positioning was significantly improved in all component parameters. Furthermore, the proportion of patients with component implantation within 2° of the initial target was significantly greater in every parameter measured [49].

Correction of alignment and ligament balancing is improved using robotic technology, as well. When using a haptic guidance system, one of this paper's authors found that the planned tibiofemoral angle could be achieved within 1°, and postoperative long leg axis radiographs were found to be within 1.6° of the preoperative plan [50]. In a case-control study comparing 40 robotic-assisted UKAs against 40 conventional UKAs, restitution of the joint line was significantly improved in the robotic-assisted group [51]. Looking at ligament balancing, Plate et al [52] demonstrated that robotic-assisted UKA was accurate up to 0.53 mm compared to the preoperative plan, and that 83% of cases were within 1 mm at all degrees of flexion tested.

Finally, a major concern surrounding UKA is the difference in accuracy and survivorship of UKAs done by experienced, high-volume surgeons vs published registry data. However, in a dry bones model, Karia et al [53] were able to show that robotic assistance allowed inexperienced surgeons to position UKA components significantly more accurately and do so repeatedly. Also, in regards to discrepancy between preoperative planning and postoperative component position, Mofidi et al [54] showed that inaccuracies related to final implant positioning were due to changes made during cementing, not the bony cuts guided by the robot. Robotic assistance clearly allows surgeons to more accurately and reproducibly control technical aspects of UKA, and may reduce outliers for both inexperienced and high-volume surgeons.

Outcomes of Robotic-Assisted UKA

Although long-term functional and survivorship data on robotic-assisted UKA have not yet become available, short-term and mid-term results appear promising. Roche et al [55] reported outcomes for the first 73 patients to receive the procedure and demonstrated average range-of-motion of 129° at 2 years and maintained at 125° at 3 years. The same authors demonstrated improvements in Knee Society Scores of 43.8 preoperatively to 96.8 postoperatively for knee scores and 63.9 to 80 for functional scores [56]. A prospective, multicenter study looking at the 2-year outcomes of 1007 consecutive patients who underwent robotic-assisted UKA found worst-case 96.0% survival at an average of 2.5 years of follow-up, with 92% of patients either satisfied or very satisfied with their knee function [57]. In a randomized, controlled trial of robotic-assisted UKA vs conventional UKA including 139 patients, those in the robotic-assisted group has better pain scores at 8 weeks and better Knee Society Scores at 3 months [58]. No differences were seen at 1 year, but over half of each cohort reached the ceiling limit of the scoring system. These early data demonstrate promising early results of robotic-assisted UKA, and support increased utilization of this technology going forward. However, long-term studies are required to make more definitive judgments about whether robotic technology improves survivorship and functional outcomes after UKA.

Conclusions

The use of robotic assistance in orthopedic surgery, and particularly in the knee, has increased significantly over the past 10 years (Boylan JOA 2017). Robotic assistance clearly improves surgeons' ability to control implant positioning, ligament balance, and limb alignment during UKA, and has led to improved survivorship at short-term follow-up. As utilization of this technology continues to increase, more mid-term and long-term studies are required to determine how robotic surgery will affect overall survivorship of UKA. Given the promising early biomechanical, radiographic, and clinical results of robotic-assisted UKA, the authors support the continued usage of this technology to maximize surgical accuracy and patient outcomes in UKA (Fig. 5).

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