Robotic-assisted Unicompartmental Knee Arthroplasty: The MAKO Experience

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KEYWORDS

• Unicompartmental knee arthroplasty • Robotic Assistance • MakoPlasty • Haptics

KEY POINTS

- This new robotic procedure provides comprehensive, 3-dimensional planning of partial knee components, including soft tissue balancing, followed by accurate resection of the femur and the tibia. This preparation allows for precise placement and alignment of the components.
- Patients have shown significant improvements in their postoperative function in every functional measurement, including more normal knee kinematics.
- The introduction of new procedures and technologies in medicine is routinely fraught with issues associated with learning curves and unknown potential complications.
- Because the specific objectives of this novel technology are to optimize surgical procedures to provide more safe and reliable outcomes, the favorable results seen to date prove this technology to be a significant improvement in the surgical technique of partial knee arthroplasty.

INTRODUCTION

In the late 1990s, Repicci and Eberle introduced a unicompartmental knee procedure using an inlay tibial component termed "minimally invasive surgery" (**Fig. 1**).[1–9] This procedure resulted in earlier mobilization, shorter inpatient stay, and shorter length of rehabilitation than had been observed for the conventional surgical approach. However, concerns were raised about loss of accuracy with minimally invasive techniques. With minimally invasive procedures, visualization is reduced leading to potential errors in implant placement, limb alignment, cement technique, and bone preparation (**Fig. 2**).[10,11]

The introduction of technology to improve accuracy of unicompartmental outcomes began with navigation. Jenny and colleagues[12] reported on a series of 60 patients who underwent navigated minimally invasive unicompartmental knee arthroplasty (UKA) and 60 patients who underwent navigated larger incision UKA. These authors cited

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Surgical Errors: Key Points to Consider

Surgical Errors are fully in the surgeons' control and have a prominent effect on implant survival. A surgeon must familiarize himself with the system of choice and perform a consistent amount of surgeries to achieve consistent outcomes. Unicompartmental Knee Replacement (UKR)s are very unforgiving to technical errors, which often lead to early postoperative failures.

Common Errors

- Overcorrection of alignment
- Flexion-extension instability
- Not achieving cortical rim coverage with the tibial tray/ or allowing overhang of components
- Patellar arthritis (grade 4) or instability
- Inset tibial poly tray may subside
- Poor cement technique
- Anterior placed femoral component

Poor visualization can lead to

- Over/under resection of tibia
- Over/undercorrection of limb alignment

Implant placement

- Tibia—under coverage of cortex, overhang
- Anterior Cruciate Ligament (ACL) injury
- Excessive slope
- Mal-rotation—internal rotation-external rotation (IR-ER) of implants
- Patellar impingement
- Cement retention
- Pin site fracture
- Retained osteophytes

the advantages of reduced surgical trauma, reliability, and safety obtained with the navigated minimally invasive procedure, whereas radiographic accuracy of implantation was the same for both minimally invasive and larger incision navigation techniques.

Justin Cobb first introduced robotic assistance in 2000 using the Acrobot robot to improve the accuracy of implant positioning during UKA.

Cobb and colleagues[13] first reported a prospective comparison of a tactile-guided robot-assisted UKA and conventional UKA performed with manual instrumentation. Their robotic system used static referencing that required rigid intraoperative fixation of the femur and tibia to a stereotactic frame. The primary outcome measurement was the angle of the tibiofemoral alignment in the coronal plane, measured by computed tomography (CT). Implant position errors relative to the planned position averaged 1.1 mm and 2.5° with robotic assistance compared with 2.2 mm and 5.5° conventionally along any axis. Overall tibiofemoral coronal plane alignment was within 2° for every case performed with robotic assistance. Only 40% of conventional surgery achieved this level of accuracy.

In 2006, MAKO Surgical Corporation obtained US Food and Drug Administration clearance to begin the first implantation of medial UKAs using a haptic-controlled passive robotic arm. This system allows an accurate surgical preparation of the

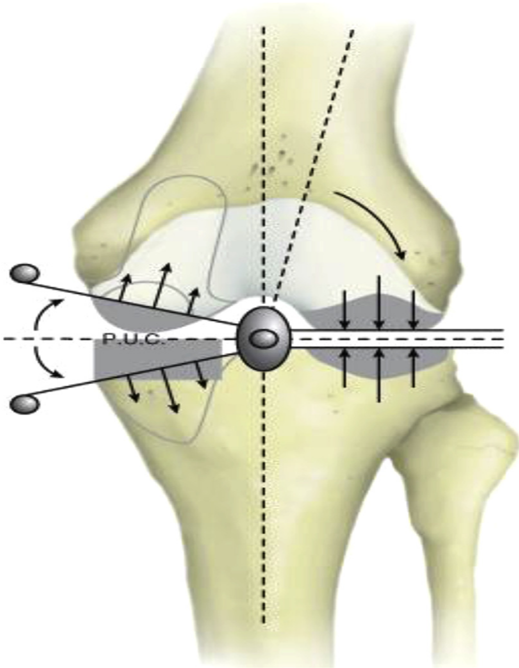

Fig. 1. The potential angular and rotation issues are depicted in unicompartmental implant placement.

specific patients' diseased knee compartment in one or multiple compartments, sparing healthy tissue in the undiseased compartments. This allows the surgeon to tailor the surgical procedure to the patient's arthritic and kinematic needs (Fig. 3). Addressing the medial, lateral, and patellofemoral joint in an individual, or modular manner, can be planned preoperatively and refined intraoperatively as the patient's knee kinematics and the disease pathology requires.

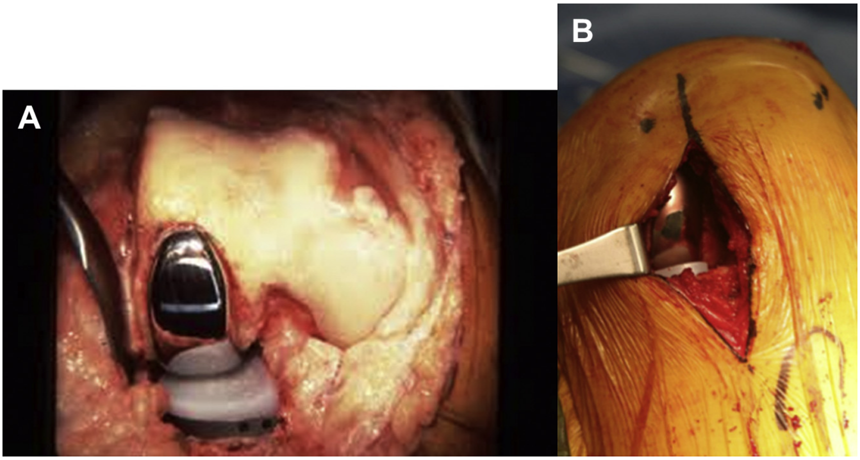

Fig. 2. Comparison of incision both approaches for (*A*) standard open and (*B*) minimally invasive implantation of UKA.

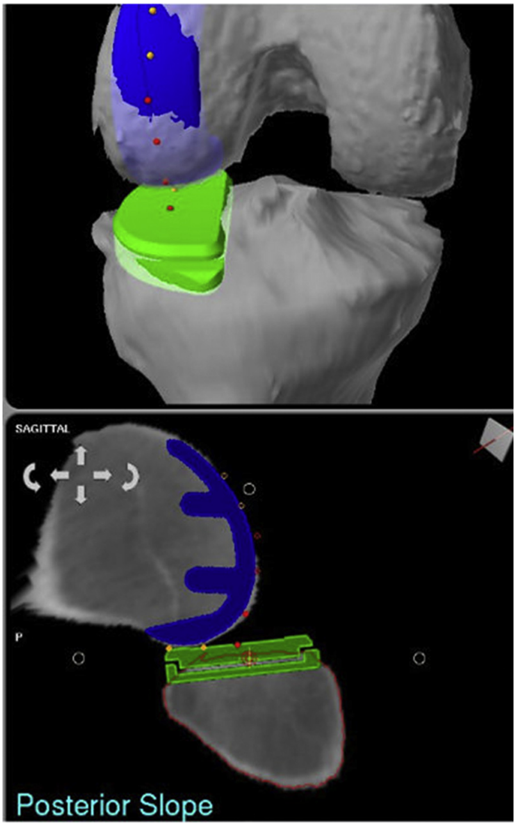

Fig. 3. The Patient's kinematic profile is evaluate on the computer screen through a full range of motion prior to burring.

Modular implants allowed inlay tibial or onlay tibial components to be used, with an anatomic femoral and trochlear implant. The implant design was based on CT-based parameters of more than 100 healthy and diseased knees. The femoral and patellofemoral components are created from a single, continuous surface. The inner geometries are contoured to allow bony preparation using a 6-mm burr. The femoral component allows deep flexion and has angled pegs to improve implant stability. The patellar component used in bicompartmental knee arthroplasty is a dome-shaped all polyethylene 3-pegged design, not pictured (Fig. 4).

The integration of robotic-arm assistance allows a surgeon to have a controlled, highly accurate system that is be integrated into the present surgical workflow. The enabling technology in this robotic platform was the development of haptics. Haptics is the science of applying touch (tactile) sensation and control to interaction with computer applications (Fig. 5). The evolution of this technology into the orthopedic arena was enabled by the ability of the surgeon to obtain an accurate reproducible surgical result in all 6 degrees of freedom (3 translational and 3 rotational), which the human eye cannot reproduce to the same level of precision.

This system uses optical motion capture technology to dynamically track marker arrays fixed to the robotic arm, femur, and tibia, allowing the surgeon to freely adjust limb position and orientation during tactile-guided bone cutting. This

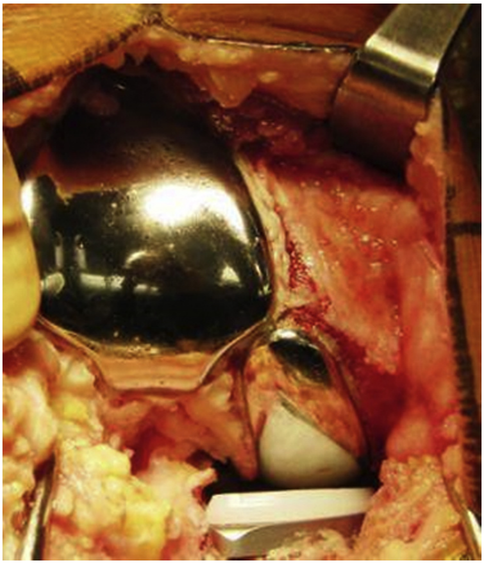

Fig. 4. The modular implants showing a medial UKR and Trochlear implant in a bicompartmental knee replacement.

robotic-assisted platform enables the surgeon to use a preoperative computer-assisted planning system and a high-speed burr controlled by a tactile guidance system intraoperatively, thus eliminating the need for conventional instrumentation.

There are several systems in place throughout the procedure to ensure accuracy is achieved. Tibial and femoral checkpoints must be verified before each section of bone is prepared. At any point throughout the procedure, the robotic-arm and mechanical burr tip can be removed from the surgical zone and a tracker probe can be used to visualize accuracy and cuts directly on the patient's CT scan (Fig. 6).

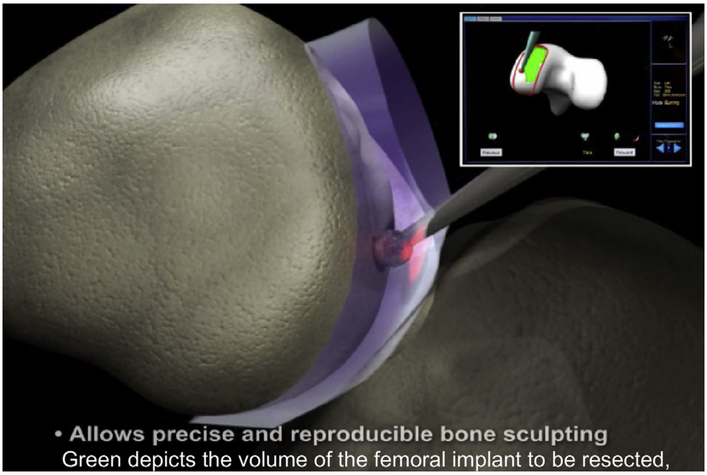

Fig. 5. Virtual bone resection shows the RIO burr in a 3-dimensional virtual haptic safe zone. Burr is only active for cutting when burr tip is within haptic safe zone.

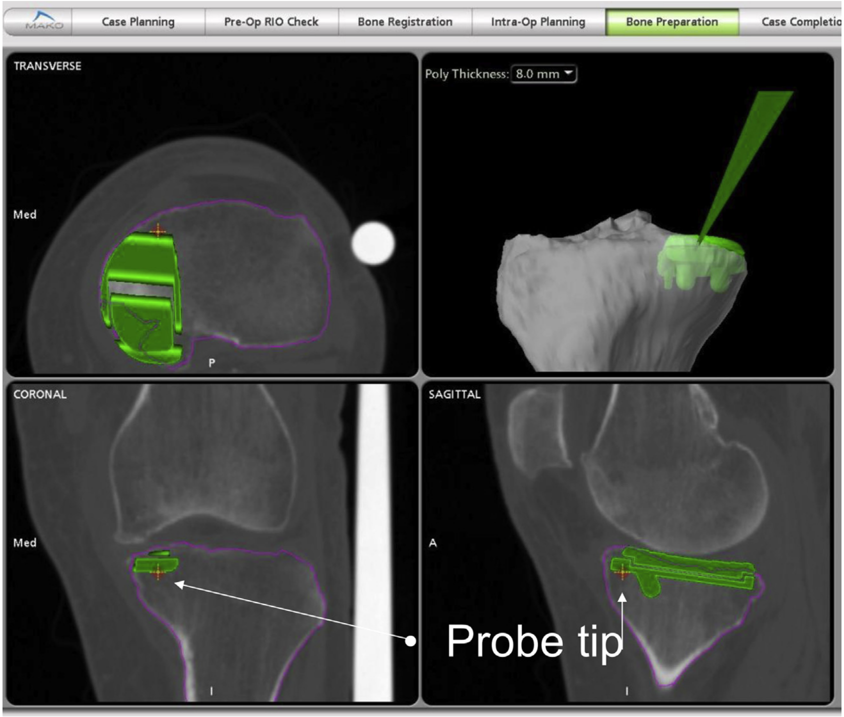

Fig. 6. Screen capture from software shows how probe confirms planned depth of cut on CT view.

During burring, the surgeon receives visual, auditory, and haptic feedback to ensure adherence to the surgical plan. Visual feedback is depicted on the user interface module. Green bone on the screen indicates bone to be removed; white bone on the screen indicates the surgeon has removed the necessary bone, and red bone on the screen depicts when the planned implant placement threshold has been penetrated up to 0.5 mm (**Fig. 7**). If penetration occurs beyond 0.5 mm, the burr tip shuts off. When approaching the implant boundaries, a surgeon receives auditory feedback with a beeping noise. Haptic feedback refers to the tactile sensation of the arm physically resisting a surgeon's applied force when the haptic boundary is approached. Boundaries are specified to match the implant shape, size, and placement based on intraoperative planning. Cement tolerances are included in boundaries.

Roche and Coon have reported the accuracy of this system in accurate implant placement. Coon and colleagues[14] radiographically compared 44 manually implanted UKAs to 33 robotically implanted. The accuracy of implant positioning with robotic-arm assistance was improved by a factor of 2.8 in the sagittal plane and an average root-mean-square (RMS) error of 3.2° in the coronal plane as compared with the accuracy of manual, jig-based instrumented UKAs.[14] Roche and colleagues[15] radiographically measured postoperative implant placement accuracy on a series of 43 UKA patients. Average RMS errors were 1.9° in the coronal plane and 1.7° in the sagittal plane. More recently, Roche and colleagues published 3-dimensional accuracy results from postoperative CT scan taken for 20 of the first 50 patients to ever receive the procedure. For this study, all average RMS errors were found to be

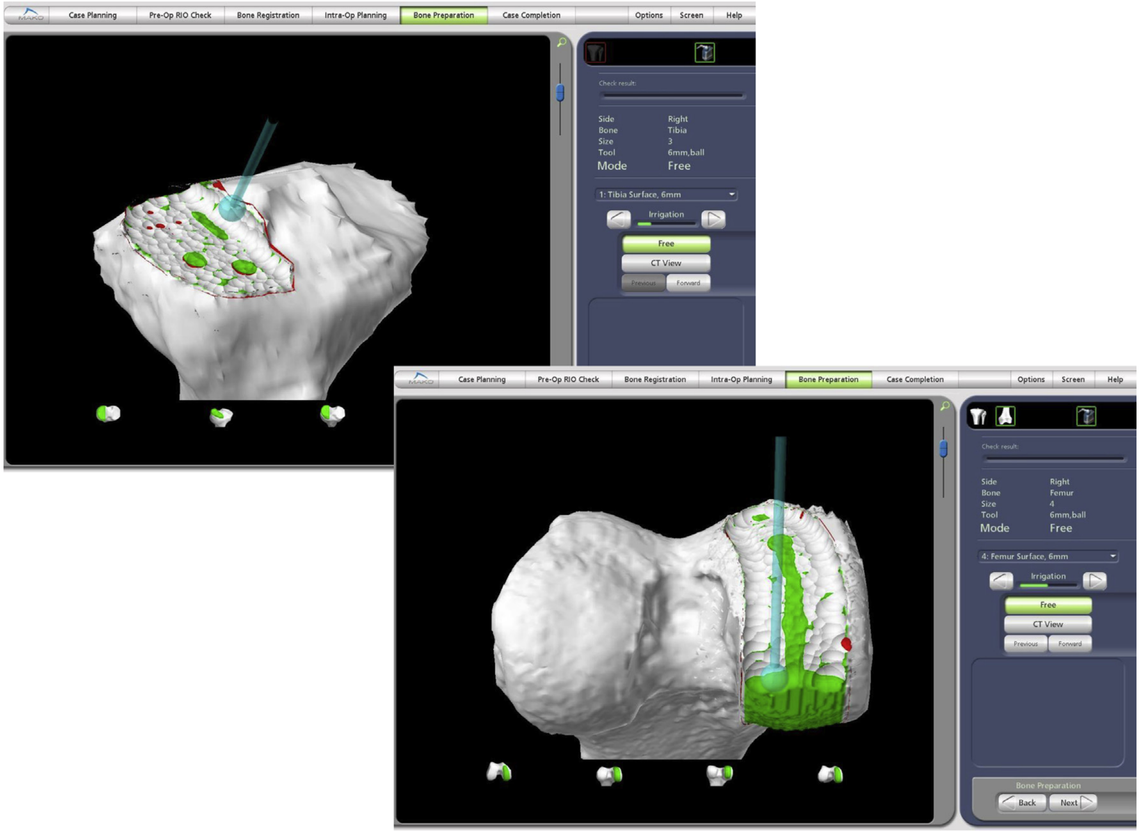

Fig. 7. Screen captures taken during burring of tibia (*left*) and femur (*right*) show bone being resected. Green bone represents bone still to be burred. Red bone indicates any cut that is made outside of 0.5 mm from the plane. The burr will shut off beyond 1 mm of planned resection.

within 1.6 mm and 3.0° in all directions. These patients demonstrated good or excellent outcomes including average Knee Society Scores (KSS) at 3 years of 88 and 75 for knee and function, respectively. At 6 weeks, the range of motion (ROM) improved from a preoperative value of 119° to 126° of flexion and was maintained at 125° out to 3 years postoperatively.[16]

Radiographs reveal precise, repeatable, and accurate implant placement (Fig. 8). These images confirm this historically difficult surgery can be performed with minimally invasive approaches, supplemented with a robotic-arm to achieve predictable reproducible results.

The proposed benefits of a robotic-assisted platform include the ability to resurface only the painful degenerative knee surfaces and retain healthy structures, which leads to improved kinematics, stability, and proprioception. Watanabe and colleagues[17] reported the kinematics for a series of 15 knees to receive partial knee replacement whereby all knees showed normal posterior lateral condylar translation while kneeling and performing a step activity. These findings more closely represented normal knee kinematics than TKA patients that underwent the same test procedure.

Although the robotic arm ensures accurate implant placement, many additional factors are required for a surgeon to achieve a successful surgical outcome. The ability to perform the predicted surgical plan consistently and precisely is related to proper implant sizing and positioning specific to the patients' anatomy, optimizing the tension/balance of the collateral and cruciate ligaments through the entire ROM, actualizing smooth implant-cartilage transitions through cartilage mapping software, and the ability to minimize bone resection and tissue injury during surgery with haptic boundaries.

Through a minimal incision, optimized implant placement and soft tissue balancing enables a rapid rehabilitation program that enables patients to return to activities of daily living or resume work with minimal recovery times.

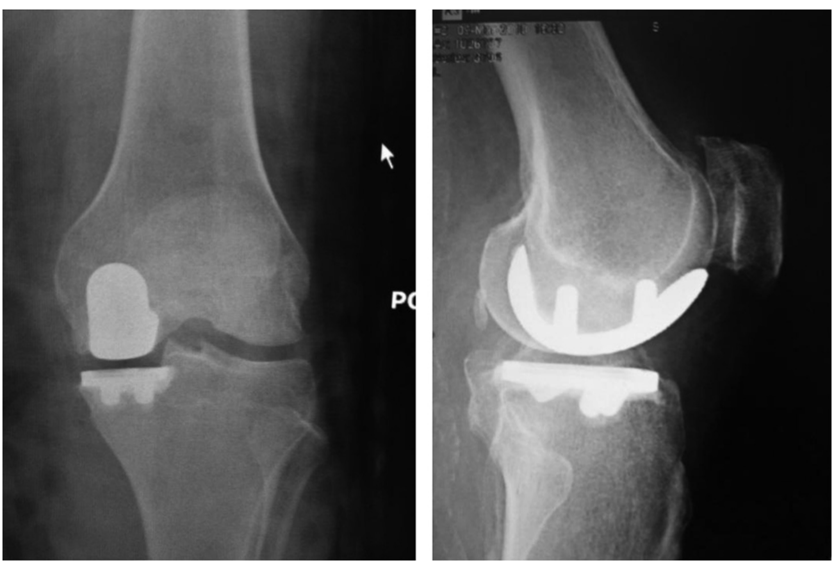

Fig. 8. Anteroposterior and lateral postoperative radiographs show precise placement of robotic-arm–assisted UKA.

CLINICAL OUTCOMES

Roche and colleagues[18] reported outcomes for the first 73 patients to receive robotic-arm–assisted UKA. There were 42 men in the group and patient's average age was 71 $\pm$ 10 years. The average body mass index for patients was 29 with 38% of the population considered obese. At 2 years postoperatively, patients saw an increased average ROM of 129° of flexion compared with a preoperative ROM of 123°. Postoperative KSS also increased from 43.8 preoperatively to 96.8 postoperatively for knee scores and 63.9 preoperatively to 80 postoperatively for their function scores.

Coon and colleagues[19] reported patient outcomes for 36 of their initial robotic-arm–assisted UKAs and compared those results with the 45 cases performed just before the introduction of robotic technology with manual instruments using a mini-invasive technique. They saw no significant difference in average knee society score (KSS), average change in KSS, or Marmor rating at postoperative follow-up. These findings suggest results are comparable with accepted technique and show there was not a detectible learning curve effect manifest in clinical outcomes with this new technology.

SUMMARY

This new robotic procedure provides comprehensive, 3-dimensional planning of partial knee components, including soft tissue balancing, followed by accurate resection of the femur and the tibia. This preparation allows for precise placement and alignment of the components. Patients have shown significant improvements in the postoperative function in every functional measurement, including more normal knee kinematics. The introduction of new procedures and technologies in medicine is routinely fraught with issues associated with learning curves and unknown potential complications. Because the specific objectives of this novel technology are to optimize surgical procedures to provide more safe and reliable outcomes, the favorable results seen to date prove this technology to be a significant improvement in the surgical technique of partial knee arthroplasty.

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