Robot-assisted unicompartmental knee arthroplasty: A critical review

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Abstract

Introduction
Unicompartmental knee arthroplasty (UKA) is an effective surgical treatment for unicompartmental arthritis. Although results can be optimized with careful patient selection and use of a sound implant design, the most important determinant of success of UKA is component alignment. Studies have shown that component malalignment by as little as 2° may predispose to implant failure after UKA. Robot-assisted UKA has been projected to address this issue, which combines patient specificity and navigation. Modern-day robots overcome the problems with older-generation robots like iatrogenic fractures and also introduce in vivo dynamic assessment of the knee that incorporates soft tissue tension. Issues with learning curve, longer operating times and high cost investment persist. We discuss the technique of one such modern robotic design and review the literature with respect to accuracy in restoring limb alignment and their functional outcome.

Conclusion
Short-term results for robot-assisted UKA are promising, although long-term results are awaited to determine implant survivorship and functional outcome.

Introduction
Unicompartmental knee arthroplasty (UKA) can provide durable pain relief and functional improvement in greater than 90% of patients with focal arthritis or osteonecrosis of the medial or lateral compartments of the knee. Concerns with UKA are early failure of the femoral or tibial components. The main cause of early failure is malpositioning of components with overcorrection or undercorrection of limb alignment. Swiencikowski and Page reported that coronal malalignment of the tibial component beyond 3° predisposed to failure. Malalignment of the femoral component has been found to cause femoral fracture, patellar impingement and tibial component loosening. In addition, excessive posterior slope (>7°) of the tibial component has been linked to tibial component loosening, anterior cruciate ligament (ACL) rupture and abnormal stress forces on the periprosthetic bone. Therefore, though UKA has many benefits, technical difficulties in achieving accurate alignment have impeded widespread adoption of this procedure by orthopaedic surgeons. As many as 40% to 60% of components may be malaligned by more than 2° from the preoperative plan with conventional methods. In a bid to improve UKA outcomes, orthopaedic surgeons have begun taking advantage of several technological innovations, including the use of computer-assisted navigation and robotics.

Navigation has been shown to improve postoperative leg alignment over that obtained in conventional UKA. Although navigation is a powerful visual aid, surgical outcomes still depend on the mechanical tools used in procedures. However, even with computer navigation, the number of outliers (beyond 2° of the preoperatively planned implant position) may approach 15%.

Recently developed robotic systems have tremendous potential to improve the outcomes of procedures such as UKA. Crucially, these new robots are ‘semi-active’; that is, the surgeon retains ultimate control of the procedure while benefiting from robotic guidance within target zones and surgical field boundaries. These zones and boundaries are determined by preoperative computed-tomography-based (CT-based) planning with continuous intraoperative visual feedback. The system incorporates navigation and robot technology. The combination allows for more accurate reproduction of the preoperative plan of implant placement, which may improve overall leg alignment and reduce iatrogenic morbidity.

The aim of this critical review was to discuss robot-assisted unicompartmental knee arthroplasty.

Discussion
Indications for robot-assisted UKA follow essentially the same criteria as for conventional UKA set by Kozinn and Scott. Low demand patients >60 years with unicompartmental arthritis.
- Weight less than 82 kg
- Minimum 90° flexion arc
- Fixed flexion deformity less than 5°
- Coronal plane correctable deformity not exceeding 10° of varus or 15° valgas
- Asymptomatic patellofemoral and tibiofemoral compartment.
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Relative contraindications are obesity, incompetent ACL (if UKA is considered, then posterior slope should be minimized) and younger patients (as an alternative to osteotomy).

One of the newer robotic design systems/software is MAKO Tactile Guidance System and the procedure is MAKOplasty that is referred to here.

Preoperative imaging

Preoperative CT scans are obtained for all patients. Scan protocol requires supine positioning with a motion rod attached to the affected leg. One-millimetre slices are taken at the knee joint, and 5-mm slices are taken through the hip and ankle. Images are saved and transferred to the software of the Tactile Guidance System so that sagittal slices of the distal femur and proximal tibia may be segmented, defined, and recombined to produce three-dimensional (3-D) models of each. Implant models are then positioned, with corresponding cement mantles on the reconstructed bone models, resulting in patient-specific CT-based planning (Figure 1).

CT-based planning is limited in that soft tissues cannot be visualized with CT. Consequently, guidance for soft-tissue balancing is lacking, only bony alignment can be used for planning, and the plan must be intraoperatively modified to achieve precise gap balancing and long-leg alignment. CT planning allows for the assessment of the subchondral bone bed, osteophyte formations, and volume definition of cysts and avascular necrosis.

Preliminary sizing of components

The preliminary plan is based on alignment parameters and 3-D visualization of implant position (Figure 1). During surgery, the plan is modified according to gap kinematic measurements and dynamic lower limb alignment values. In addition, more than 7° of posterior slope of the tibial component has been shown to increase the risk for ACL rupture8. We therefore recommend placing the tibial components in 2° to 4° of varus and avoiding more than 7° of posterior slope. In patients with ACL deficiency, the posterior sagittal slope of the tibia is maintained between 2° and 5°. Three-dimensional visualization of implant position ensures proper sizing. For example, we advocate a 2-mm rim of bone surrounding the pocket created for the inlay tibial component. This rim can be planned and measured directly on the 3-D model. On the femur, the prosthesis is sized such that coverage is maintained while symmetric flexion and extension gaps are created. In addition, depth of resection can be planned precisely; 3 mm of tibial bone resection is typically planned. This resection depth can be modified according to intraoperative gap kinematics.

Operative setup and robot registration

After conventional positioning and sterile draping of the affected limb, robot registration is performed (Figure 2). The surgeon moves the robotic arm through a defined 3-D path to calibrate its movements and set the centrepoint for the cutting instrument. The femoral and tibial reference arrays are then attached. Bone pins are placed in the femur and tibia, and optical arrays are securely attached. The camera is now positioned to track the robot and leg arrays through all ranges of motion (ROMs). Anatomical surface landmarks are registered before the skin is incised, and the leg is put through full ROM while the appropriate varus load is applied on the joint. After skin incision, small juxta-articular check-point pins are inserted on the tibia and femur, and the two bone surfaces are registered at these points.

Exposure and bone registration

The knee is exposed through a medial parapatellar skin incision for a varus knee that extends from the superior pole of the patella to just medial to the tibial tubercle. The joint is exposed by medial parapatellar arthroscopy.

The femur registration starts with 32 spheres visible on the screen (Figure 3). The surgeon has to place...
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the tip of the blue probe (corresponding to the colour of the large spheres) to the point on the bone corresponding to one of the larger spheres displayed on the screen that then turns white if verified correctly with an accuracy of 1 mm. Similarly, the tibial registration is carried on that requires the user to acquire six points along the tibial tuberosity.

Dynamic assessment

After intraoperative registration of bony anatomy, a dynamic soft-tissue gap balancing algorithm is initiated. Varus deformity is manually corrected with application of a valgus force to the knee, while lower limb alignment is simultaneously monitored and recorded by the navigation system (Figures 4 and 5). As the virtual components are optimized to fill the space necessary to correct this deformity, the final lower limb alignment is reliably predicted. We target final lower limb alignment of approximately 2° of varus. The limb is moved from extension to flexion in a smooth manner with gentle valgus correction making sure to capture at least five completed poses in the arc (Figures 6 and 7). The Joint Balancing page facilitates capture of live limb alignment for use in implant planning. The flexion/extension angle, varus/valgus angle and internal/external rotation values of the leg/implant plan are displayed on the screen.

Graph display

The graph displays a visual representation of the tightness or looseness of the knee at captured pose angles (Figure 8). The graph shows that the knee is loose in all poses from extension to 90° flexion. Moving the femoral component inferiorly in the sagittal plane on the screen will tighten the extension gap (Figure 9). Similarly, moving the femoral component posteriorly will tighten the flexion gap (Figure 10). The graph appears loose only in midflexion.
Resection of the bone surface can be accomplished with the 6 mm or 2 mm ball burrs, depending on the chosen implant system. All implant posts are resected using the 6 mm Ball Burr; the Onlay keel is resected using the 2 mm router. CT view allows the user to use the tip of the active burr or tracked probe to investigate real-time correlation of resection positions relative to the pre-operative plan, the CT data and the patient anatomy.

When active, the CT view screen will display a transverse, sagittal, coronal and 3-D view of the CT data and implant model with a live update of any active probe or burr.

Once the bone is prepared, trial components are inserted and stability is verified in all ranges of motion. Dynamic long-leg alignment is displayed on the computer monitor so that final alignment can be tracked. Finally, once the implant is satisfactorily positioned, both implant components are cemented (Figure 15) and a final ROM of the knee joint is executed so that original, trial and final implant kinematics and knee alignment can be compared. Before site closure, the mini-checkpoints and bone reference arrays are removed. Postoperative radiographs are taken to assess component positioning (Figures 16 and 17).

UKA can be performed using conventional, navigation or more recently the robotic technique. Berger and colleagues found that the implant survival rate for 62 consecutive UKAs performed with cemented modular Miller–Galante implants was 98% after 10 years and 96% after 13 years, using revision and radiographic loosening as the respective endpoints. The survival rate was 100% at 13 years with aseptic loosening as the end point.
Price and colleagues\textsuperscript{19} reported 10-year all-cause implant survival with an Oxford mobile-bearing medial UKA of 91% in patients younger than 60% and 96% in patients 60 or older.

The main issue with the conventional techniques is its reproducibility. As previously stated, 40% to 60% of cases involving conventional methods may have alignment that is off by more than 2° from the preoperative plan (Figure 2). In addition, range of component alignment varies considerably, even among cases managed by skilled knee surgeons\textsuperscript{24}.

A study by Collier et al.\textsuperscript{20} found that of 245 medial UKAs, the mean tibial component varus was $8 \pm 3$ (range, $-5$ to $+21$) and the mean posterior tibial component slope was $9 \pm 4$ (range, $-2$ to $+21$).

Recently, minimally invasive techniques have achieved an overall reduction in soft tissue and bone trauma; however, it has been noted that minimal invasive techniques are not as accurate as open UKA with regard to the anteroposterior-tibial placement and the postoperative leg alignment and overall revision rate\textsuperscript{21–23}. According to an analysis of the results of 221 consecutive UKAs performed through an MIS approach, the range of tibial component alignment was large ($18°$ varus to $6°$ valgus; mean $6°$; SD 4°)\textsuperscript{23}. In a series by Fisher et al.\textsuperscript{22}, there was a statistically significant difference in the coronal alignment of the tibial component in UKA performed with a minimally invasive technique compared with a standard open technique with a medial parapatellar arthrotomy ($84.6 \pm 2.8$ [range, 78–97] compared with $85.9 \pm 2.1$ [range, 80–92], respectively; $p = 0.001$).

Computer navigation was introduced to UKA to reduce the number of outliers and improve accuracy, but the percentage of outliers (>2° from the planned implant position) may still approach 15%\textsuperscript{10}.

Emerson and Higgins\textsuperscript{18} reporting their personal experience with 55 mobile-bearing Oxford UKAs, noted a 90% rate of 10-year implant survival with progression of lateral compartment arthritis as the endpoint and 96% with component loosening as the endpoint.

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History of robotic knee dates to the year 2000. The initial robots had limitations due to which it went out of vogue. Drawbacks of these robotic systems include the necessity for an invasive frame connecting the robot and patient, thus limiting free motion throughout the surgical procedure. In addition, frame fixation has been shown to be problematic, associated with an expanded approach, local infections and even iatrogenic fractures.

The robot needed to be rigidly fixed to the patient’s bony anatomy. This led to complications such as infection, iatrogenic fractures or soft tissue injury, because of the robot’s weight and movement. In addition, another drawback of rigid fixation is a potential reduction in the scope of the approach to the knee and intrusion into the surgical field.

Modern day robots are independent of the patient’s positioning or movement. Therefore, there is no further rigid fixation device necessary. Also, there is greater precision in burring of the bony surface compared with regular UKA cutting guides. The surface flatness of tibial bone cuts prepared by a robot-assisted procedure ranged between 0.15 and 0.29 mm versus 0.16 and 0.42 mm during conventional surgery using an oscillating saw. This difference in favour of robot-assisted surgery is clinically important, because the maximal distance between the bone and the prosthetic component that allows bone ingrowth to occur is 0.3 to 0.5 mm\textsuperscript{24–26}. It permits the creation of individual bony surfaces of any shape, which cannot be generated by an oscillating saw. Consequently, a press-fit cavity for the implant can be created. Thus, preservation of the remaining bone surface is possible, which can be very useful for revisions and conversions to total knee prosthesis.

The present generation robots also allow for assessment of dynamic correction of deformity that mimics

![Figure 9: Femoral component moved inferiorly to tighten knee extension.](image)

![Figure 10: Femoral component moved posteriorly to tighten knee at 90° flexion.](image)
the total improved from 41 to 21; pain improved from 8 to 4; stiffness improved from 4 to 2; and physical function improved from 29 to 15.

Lonner\textsuperscript{29} compared the postoperative radiographic alignment of the tibial component with the preoperatively planned position in 31 knees in 31 consecutive patients undergoing UKA using robotic arm-assisted bone preparation and in 27 consecutive patients who underwent unilateral UKA using conventional manual instrumentation to determine the error of bone preparation and variance with each technique. Radiographically, the root mean square error of the posterior tibial slope was 3.1° when using manual techniques compared with 1.9° when using robotic arm assistance for bone preparation. In addition, the variance using manual instruments was 2.6 times greater than the robotically guided procedures. In the coronal plane, the average error was 2.7 ± 2.1 more varus of the tibial component relative to the mechanical axis of the tibia using manual instruments compared with 0.2 ± 1.8 with robotic technology.

Pearle\textsuperscript{30} in his series of 10 cases of robot-assisted UKA concluded that the difference between planned and intraoperative tibiofemoral angle was within 1° and the postoperative long leg axis radiographs were within 1.6°.

There are limitations with this procedure. The overall costs of the system are high, excluding additional costs for CT scanning and regular maintenance of the robot. It is also necessary to use additional skilled personnel in the OR. Finally, CT-based systems fail to incorporate soft tissue tension into the planning. Gap kinematics, however, are tracked intraoperatively by tracking a manual flexion/extension cycle of the knee before the burring process. The implant placement can be refined based on the predicted gaps; this soft tissue balancing process is distinct from traditional practices, and its reliability accurately \textit{in vivo} ligament tension and accordingly adjust the final implant positioning to obtain a well-balanced knee in all ranges of motion.

Cobb et al.\textsuperscript{9} were able to demonstrate, in a prospective clinical study, a significant improvement in implant placement, and that accurate leg alignment can be achieved successfully with the aid of a semi-active (Acrobot) robot system in UKA.

Coon\textsuperscript{27} showed results in comparison of 35 robotic cases with 45 conventional ones and found the accuracy of the tibial implant slope to be 2.5 times better ($p < 0.05$), varus alignment to be 3.2° better ($p < 0.05$) and SD to be 2.8 times less ($p < 0.05$) in the robotic arm group.

Roche\textsuperscript{28} and colleagues\textsuperscript{11} reported on their first 43 patients. The range of motion increased from 121° to 126°; KSS improved from 95 to 150; and Medical Outcomes 12-Item Short Form Survey (SF-12) Physical Summary scores improved from 19 to 30. Regarding WOMAC scores, the total improved from 41 to 21; pain improved from 8 to 4; stiffness improved from 4 to 2; and physical function improved from 29 to 15.
is unknown. Mid- and long-term follow-up is not available given the recent adoption of this technology. Further follow-ups will be necessary to determine whether the reduction in alignment errors that we observed with robotic arm-assisted bone preparation will ultimately influence implant function or survival.

**Conclusion**

Robot-assisted UKA allows surgeons to prepare a patient-specific CT-based preoperative plan that can be executed precisely. The surgical field is predefined, and inadvertent deviation outside the field is prevented by active constraints of the robotic arm, thus minimizing iatrogenic morbidity and maximizing bone preservation. Burr ing of the exact cavity of interest for the specific implants allows for greater conservation of bony surfaces during arthroplasty. Although results are preliminary, dramatically improved surgical accuracy and improved ligament dynamics do show a promising trend for its continued use in the future. Short-term results are encouraging and clinical trials to determine long-term efficacy with respect to functional outcome and implant survivorship are necessary.

**References**

5. Sandborn PM, Cook SD, Kester MA, Haddad RJ Jr. Fatigue failure of the femoral...

**Figure 13:** Image after burring of the distal femur.

**Figure 14:** Image after burring of the tibial plateau.

**Figure 15:** Insertion of the final components.