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Robotic technology: current concepts, operative techniques and emerging uses in unicompartmental knee arthroplasty

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- Unicompartmental knee arthroplasty (UKA) is associated with improved functional outcomes but reduced implant survivorship compared to total knee arthroplasty (TKA).
- Surgeon-controlled errors in component positioning are the most common reason for implant failure in UKA, and low UKA case-volume is associated with poor implant survivorship and earlier time to revision surgery.
- Robotic UKA is associated with improved accuracy of achieving the planned femoral and tibial component positioning compared to conventional manual UKA.
- Robotic UKA has a learning curve of six operative cases for achieving operative times and surgical team comfort levels comparable to conventional manual UKA, but there is no learning curve effect for accuracy of implant positioning or limb alignment.
- Robotic UKA is associated with reduced postoperative pain, decreased opiate analgesia requirements, faster inpatient rehabilitation, and earlier time to hospital discharge compared to conventional manual UKA.
- Limitations of robotic UKA include high installation costs, additional radiation exposure with image-based systems, and paucity of studies showing any long-term differences in functional outcomes or implant survivorship compared to conventional manual UKA.
- Further clinical studies are required to establish how statistical differences in accuracy of implant positioning between conventional manual UKA and robotic UKA translate to long-term differences in functional outcomes, implant survivorship, complications, and cost-effectiveness.

Keywords: functional outcomes; implant positioning; limb alignment; robotics; unicompartmental knee arthroplasty

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Introduction

Unicompartmental knee arthroplasty (UKA) is an effective surgical procedure for end-stage single-compartment knee osteoarthritis.[1] It is currently performed in over 10,000 patients per year in the United Kingdom.[2] The first recorded UKA was performed by Campbell et al in 1940, although since then the procedure has undergone several modifications. Changes have been made to the surgical approach, operative indications, implant design, implant material, bearing surface, and surgical instrumentation in order to improve the outcomes and the efficiency of the procedure.[3–8] Advantages of UKA over total knee arthroplasty (TKA) include reduced operative time, decreased intraoperative blood loss, reduced periarticular soft tissue trauma, improved preservation of native bone stock, better restoration of native kinematics, increased patient satisfaction, and improved functional outcomes.[4–9] Furthermore, UKA is associated with reduced length of hospital stay, faster return to sporting and work activities, and better quality of life scores, which lead to improved cost-effectiveness and better resource use compared to TKA.[6–8,10,11] Despite these advantages, UKA is often less favoured due to its association with reduced implant survivorship and increased revision rates when compared to TKA.[12,13] Existing registry data has also shown that surgical errors in implant positioning and suboptimal limb alignment are the most common reasons for implant failure and early revision surgery in UKA.[5–7] To help overcome this, there has been a recent surge in robotic UKA. This procedure uses computer technology to preoperatively plan optimal bone resection and implant positioning, and employs an intraoperative robotic device to execute this plan with a high level of accuracy.[14–17] This review article provides an overview of the limitations of conventional manual UKA, discusses the operative stages of robotic UKA, explores the different types of robotic UKA systems in practice, and details how robotic UKA impacts accuracy of implant positioning, functional outcomes, implant survivorship, and cost-effectiveness compared to conventional manual UKA. The limitations of robotic UKA are discussed and gaps in the existing medical literature are highlighted to aid future research.

Limitations of conventional jig-based UKA

Preoperative radiographic two-dimensional (2D) templating and intraoperative alignment guides are used in conventional manual UKA to help plan and perform error-free bone resection and implant positioning. However, this technique is associated with limited accuracy and poor reproducibility of achieving the planned component positioning, owing to inter-patient variations in anatomical landmarks for referencing, subjective assessments of optimal jig positioning, and lack of objective intraoperative data on limb alignment.[15,18,19] Suboptimal pin placement into the tibial cortex, re-drilling guide pins, iatrogenic bone and soft tissue injury from the hand-held sawblade, and suboptimal mediolateral tibial component positioning may lead to stress fractures and/or bone collapse, requiring complex revision surgery.[15,18,19] The manual technique for UKA also relies on several subjective intraoperative assessments of kinematics including the arc of flexion, limb alignment, and periarticular soft tissue tension, to guide bone resection and fine-tune implant positioning. Due to these reasons, conventional manual UKA is heavily dependent on the skill and expertise of the operating surgeon. Liddle et al reviewed outcomes of 37,131 UKAs from the National Joint Registry for England and Wales, and found surgical case-volume strongly influenced implant survivorship following UKA.[20] For surgeons performing fewer than ten UKAs per year, the mean eight-year rate of UKA survival was 87.9% (95% confidence interval [CI] = 86.9% to 88.8%) compared with 92.4% (95% CI = 90.9% to 93.6%) for those who performed 30 UKAs or more per year.

Surgical technique

Robotic UKA uses computerized systems at several distinct stages for accurate execution of the patient-specific surgical plan.[14–16] Preoperative plain radiographs or computerized tomography (CT) scans of the knee joint are used to create a virtual three-dimensional reconstruction of the patient's native knee anatomy. The patient-specific reconstruction is then used by the surgeon to plan an implant position and size that best achieves the desired bone coverage, component position, and limb alignment. Computer software is used to calculate optimal femoral and tibial bone resection windows for an accurate execution of this surgical plan. Intraoperative bone registration and verification of bony landmarks are used to confirm the patient's osseous knee anatomy prior to bone resection. In CT-based robotic knee systems, the patient-specific model of the knee joint is mapped intraoperatively to confirm bone geometry. In CT-free robotic application systems, registration is performed by mapping the patient's osseous anatomy onto a generic virtual model of the knee joint, and planning of implant positioning and bone resection is performed intraoperatively. The surgeon then uses the robotic device to undertake the planned femoral and tibial bone resections within the confines of the preoperative surgical plan. Optical motion-capture technology is used to assess intraoperative flexion and extension gaps, joint stability, range of movements, and limb alignment. This allows the surgeon to make live, on-table modifications to the implant position and bone resections, and permits fine-tuning of soft tissue releases to achieve the desired bone coverage, component positioning, knee kinematics, and limb alignment.[14–16]

Types of robotic UKA systems

Robotic UKA systems are classified as either fully active or semi-active depending on the degree of control that the robotic device provides the operating surgeon. Fully active robotic systems are able to carry out the planned femoral and tibial bone resections autonomously. This process is overseen and guided by the surgeon, who may activate an emergency deactivation if necessary. The Acrobot System (The Acrobot Co. Ltd., London, UK) is an example of a hands-on robotic device that delivers more accurate implant positioning and limb alignment compared to conventional manual UKA.[16] Semi-active robotic systems provide live intraoperative feedback to limit deviation from the preoperative surgical plan; however, the surgeon retains overall control over bone resection and implant positioning. The Navio Surgical System (Smith & Nephew, Andover, Texas, USA) is an example of an imageless, semi-active robotic system.[21] With this system, the surgeon initially maps out the patient's osseous anatomy onto a generic virtual three-dimensional (3D) model of the knee joint, which is then used to plan optimal bone resection and component positioning. A hand-held robotic platform helps to execute this plan with a high level of accuracy. The Mako Robotic Arm

Interactive Orthopaedic system (Stryker Ltd, Kalamazoo, MI, USA) is an example of an image-guided semi-active robotic system.[22] It differs from the Navio System by using a preoperative CT scan to create a virtual patient-specific computer-aided design model, which the surgeon then uses to plan optimal bone resection and implant positioning. A robotic arm with audio, tactile, and visual feedback assists the surgeon to execute the plan within the confines of the haptic boundaries for femoral and tibial bone resections. Optical motion-capture tracking is used to assess knee kinematics through the arc of flexion and helps guide fine-tuning of bone resections and implant positioning.[15,23,24]

Accuracy of implant positioning

Robotic technology uses the combination of preoperative virtual 3D reconstructions and an intraoperative robotic device that helps to actively control the motor function of the operating surgeon, to help reduce surgeon-induced errors in component positioning and limb alignment.[14–17] Cobb et al conducted a prospective randomized study of 27 patients with medial compartment knee osteoarthritis undergoing conventional manual UKA versus robotic UKA.[16] The authors reported that all patients undergoing robotic UKA had tibiofemoral alignment in the coronal plane within 2° of the planned position, compared with only 40% in those undergoing conventional manual UKA. Bell et al performed a prospective randomized controlled study assessing accuracy of implant positioning using postoperative CT scans in 62 robotic UKAs versus 58 conventional UKAs, and found robotic UKA reduced root mean square errors in achieving planned femoral and tibial implant positioning.[14] Herry et al retrospectively reviewed plain radiographs in 40 conventional manual UKAs versus 40 robotic UKAs, and found robotic UKA improved accuracy in restitution of the native joint line compared to conventional manual UKA.[17] Iñiguez et al assessed the accuracy of implant positioning in 27 cadaveric specimens undergoing conventional manual UKA versus robotic UKA.[25] The authors reported that robotic UKA was associated with improved accuracy of femoral and tibial component positioning, and more accurate prediction of the femoral component size than conventional manual UKA. Precision bone cuts and improved accuracy of implant positioning with robotic technology may help to facilitate reliable cementless fixation of components in future UKA designs, and also increase long-term implant survivorship compared to conventional manual UKA.[15,20] Due to the relative novelty of this procedure, there remains a paucity of data on how improved accuracy of implant positioning and limb alignment in robotic UKA translates to long-term functional and implant survivorship compared to conventional manual UKA.

Learning curve of robotic UKA

Studies have shown well-established learning curves for UKA, with the introduction of new component designs, minimally invasive surgery, computer-navigation, and patient-specific implants.[26–28] The learning curve for robotic UKA is important for understanding the impact of this procedure on the surgical workflow, scheduling of operative cases and theatre lists, and establishing any additional risks or complications during the acquisition of surgical proficiency. Kayani et al conducted a prospective cohort study on 60 patients undergoing conventional manual UKA followed by 60 patients receiving robotic UKA and used cumulative summation (CUSUM) analyses to assess incremental changes in study outcomes until surgical proficiency was achieved.[15] Robotic UKA had a learning curve of six operative cases for achieving operative time and surgical team comfort levels comparable to conventional jig-based UKA, but there was no learning curve effect for achieving the planned femoral and tibial implant positioning. There was no additional risk of complications compared to conventional jig-based UKA during the learning phase. These findings are important as they suggest that low case-volume UKA surgeons may be able to achieve high levels of accuracy in implant positioning, which has previously been a limitation of conventional manual UKA.[7,20,29] Liddle et al reviewed outcomes of 41,986 UKAs from the National Joint Registry for England and Wales and found that optimal outcomes (as assessed using revision rates) were achieved when UKA comprised 40% to 60% of the surgeon's practice.[29] Acceptable outcomes were achieved when at least 20% of practice encompassed UKA, while surgeons with the lowest usage (less than 5%) had the highest revision rates. However, achieving the optimal UKA case-volume is challenging owing to limitations in the number of patients with single-compartment knee disease and strict inclusion criteria for conventional manual UKA.[7,20,29] Robotic technology provides an avenue for low-volume UKA surgeons to achieve high levels of accuracy in implant positioning, which may help to reduce the burden of revision surgery following UKA.

Bone preservation

More conservative bone resection is associated with reduced bone oedema, decreased postoperative pain, and faster rehabilitation following UKA.[30–33] Preservation of the native bone stock is also important for aiding future revision surgery. In robotic UKA, bone resection is confined to the boundaries of the preoperative surgical plan, which helps to limit iatrogenic bone injury and better control the depth of bone resection compared to conventional manual UKA.[14,15] Ponzio et al conducted a retrospective review of 8,421 robotic-arm-assisted UKAs versus

27,989 conventional manual UKAs from a range of manufacturers. They found that 15.5% of conventional cases were associated with more aggressive tibial resection with tibial inserts greater than 9 mm used, compared with only 6.4% of robotic-assisted cases ($p < 0.001$).[34] Despite this, caution should be taken in interpreting these findings as the size of the bone resections were not recorded, and the depths of the resections were estimated using the component sizes implanted.

Soft tissue balancing

Achieving correct soft tissue tensioning and ligamentous balancing are important technical objectives for optimizing stability and long-term functional outcomes in UKA.[7,8,10,20,29] In conventional manual UKA, assessment of the periarticular soft tissue tension and limb alignment are performed manually, which is dependent on subjective assessments performed by the operating surgeon. Robotic UKA uses optical motion-capture technology to provide real-time medial and lateral gap measurements while applying valgus and varus strain to appropriately tension the ligaments through the arc of flexion. Robotic systems allow intraoperative assessments of the soft tissue balance in degrees and/or millimetres whilst reducing the deformity through the arc of knee flexion with different joint positions. This live, patient-specific, intraoperative kinematic data may be used to predict limb alignment and periarticular soft tissue tension after removal of osteophytes and prior to performing any bone resections. Bone resection, implant positioning, and implant sizing are then fine-tuned to achieve the desired ligamentous tension and limb alignment through the arc of flexion.[33,35] In UKA or high tibial osteotomy, this technology offers an avenue for executing the planned alignment with improved accuracy and reduces the risks of overcorrection or overtightening of the native compartments. More recently, optical motion-capture technology during robotic TKA has been used as an investigative tool to assess the effects of specific ligamentous releases on flexion–extension gaps, mediolateral soft tissue laxity, limb alignment, and fixed flexion deformity in patients undergoing TKA.[36] Shalhoub et al recently reviewed gap measurements in 120 patients undergoing robotic TKA combined with an intraoperative tensioning device, and found mediolateral gap balance within 2 mm across the flexion range was achieved in over 90% of patients.[37]

Functional outcomes

Robotic UKA is known to limit the action of the milling burr or sawblade to the confines of the preoperative surgical plan for bone resection.[14,15] Conceptually, this helps to reduce periarticular soft tissue injury and limit the associated localized inflammatory response compared to conventional manual knee arthroplasty.[23,38] Kayani et al performed a prospective cohort study of 146 patients undergoing conventional manual UKA versus robotic UKA, and found robotic UKA was associated with reduced postoperative pain, decreased opiate analgesia consumption, reduced inpatient physiotherapy, and decreased mean time to hospital discharge (42.5 ± 5.9 hours vs. 71.1 ± 14.6 hours respectively, $p < 0.001$) compared to conventional manual UKA.[33] Blyth et al conducted a prospective randomized controlled trial with 139 patients undergoing conventional UKA versus robotic UKA, and reported median pain scores from postoperative day one to week eight after surgery. The scores of the robotic UKA group were 55.4% lower than the conventional manual UKA group.[39] This information is valuable as many arthroplasty centres are now moving towards day case UKA.[9,40] Robotic technology offers an avenue for improved pain control, enhanced functional rehabilitation, reduced need for physiotherapy, and earlier time to hospital discharge, which may facilitate the more widespread uptake of UKA as a day case procedure.

Existing studies have not demonstrated any differences in middle- to long-term functional outcomes in conventional manual UKA versus robotic UKA. In the aforementioned randomized control trial by Bell et al, robotic UKA was associated with improved American Knee Society Scores for three months following surgery, but there was no difference in functional outcomes between the conventional and robotic groups one year postoperatively.[14,39] The authors targeted the 35 most active patients included in the study, and further evaluation of these particular patients revealed that robotic UKA improved Knee Society Scores (KSS), Oxford Knee Scores, and Forgotten Joint Scores compared with conventional manual UKA at two years follow-up. More recently, Canetti et al conducted a study to review the outcomes of 28 highly active patients undergoing lateral compartment UKA, and discovered that robotic UKA enabled markedly earlier mean return to sporting activity compared with conventional UKA (4.2 ± 1.8 months vs. 10.5 ± 6.7 months respectively, $p < 0.01$).[41] These studies suggest that robotic UKA improves short-term functional outcomes in highly active patients, although overall functional outcomes are similar to those of conventional jig-based UKA.[14,33,39,41] Zhang et al recently performed a meta-analysis using 11 studies with 498 patients undergoing robotic UKAs versus 589 patients receiving conventional manual UKAs.[42] The study found that robotic-assisted UKA was associated with lower complication rates (relative risk (RR)): 0.62, 95% CI: 0.45–0.85; $P = 0.0041$) and improved knee excursion during weight acceptance (standardised mean difference (SMD)): 0.62, 95% CI: 0.25–1.00; $P = 0.001$). There were no significant differences in patient-reported outcome measures, range of motion, and revision rates between conventional manual UKA versus robotic UKA. Similarly, Wong et al compared the outcomes of 118 conventional manual UKAs with 58 robotic UKAs, and reported no difference in KSS, Western Ontario and McMaster Universities Arthritis Index (WOMAC) or Short Form Health Survey of 12 items (SF-12) scores at a minimum of two-years post-surgery.[43]

Implant survivorship

Suboptimal limb alignment with overcorrection may lead to increased load on the unsurfaced compartments and accelerate the time to revision surgery.[15,18,19] Intraoperative optical motion-capture tracking enables the surgeon to accurately assess intraoperative limb alignment and precisely execute the optimal limb alignment. Conceptually, this may help to limit disease progression in the unsurfaced compartment and improve long-term implant survivorship. Pearle et al conducted a prospective, multi-centre review of 1,135 robotic UKAs and found that these patients had an implant survivorship of 98.8% at minimum of 22 months follow-up.[44] This is superior to the implant survival rates of conventional manual UKA reported in the national joint registries of the United Kingdom (95.6%), Sweden (95.3%), Australia (95.1%), and New Zealand (96.1%).[45–48] In a retrospective study by Batailler et al, 80 conventional UKAs were compared with 80 robotic UKAs, and revision rates in the robotic cohort were found to be 5% compared with 9% in the conventional group, although this difference was not statistically significant.[49] Notably, 86% of the revisions in conventional manual UKA were due to component malposition or limb malalignment, whereas in the robotic group, there were no revisions due to incorrect component placing. Vakharia et al reviewed outcomes in 13,617 robotic UKAs versus 21,444 conventional manual UKAs, and found implant survivorship was 100% in the robotic group compared to 97.5% in the conventional group at one-year follow-up.[50] Similarly, Cool et al reported reduced revision rates in robotic UKA (0.81% [2/246] vs. 5.28% [26/492]; $P = 0.002$) compared to conventional manual UKA at two-year follow-up.[51] In 2019, the Australian Joint Registry reported cumulative revision rates for robotic UKA at 2.8%, compared to 4.6% for non-robotic UKA at a three-year follow-up.[47] Robotic-assisted UKA was associated with reduced revisions for implant loosening, progression of disease, residual pain, and fracture, but increased revisions for infection compared to non-robotic UKA. The results of multi-centre studies and longer-term joint registry data on implant survivorship and revision rates comparing non-robotic UKA versus robotic UKA are awaited.

Cost-effectiveness

Moschetti et al analysed the cost-effectiveness of conventional manual UKA versus robotic UKA using a Markov decision analysis model. The system was cost-effective when 2-year failure rates were under 1.2% in robotic UKA, and under 3.1% in conventional UKA.[52] The authors reported robotic UKA to be a more cost-effective procedure only if the case-volume for this procedure exceeded 94 cases per year. Clement et al also performed an economic evaluation of robotic UKA in the United Kingdom by comparing quality-adjusted life years (QALY) in patients with medial compartment disease undergoing robotic UKA, conventional manual UKA, and TKA.[53] The overall health gain per patient was 13.59 QALYs after robotic UKA, 11.80 QALYs after TKA, and 12.20 QALYs after conventional manual UKA. Robotic UKA was found to be a more cost-effective intervention, with a cost per QALY relative to TKA and conventional manual UKA of £1,395 and £1,170, respectively. The shorter length of stay associated with robotic UKA significantly influenced the observed differences in QALYs, with day case procedures markedly reducing costs in this group compared to conventional manual UKA and TKA groups. Higher-volume centres achieved lower costs per QALY, in comparison to lower-volume centres, indicating that the procedure becomes more cost-effective with increased volume of cases. Further high-quality trials are required to determine the cost-effectiveness of robotic UKA compared to conventional manual UKA to help clinicians and healthcare managers make more informed decisions about implementing robotic technology into routine UKA practice.

Limitations

Robotic UKA is associated with substantial costs for purchasing the robotic device, additional preoperative CT scanning, further training for surgical staff, and increased operative times during the initial learning phase.[15,54] Many robotic devices are also only compatible with specific implants and therefore additional costs for purchasing supplementary equipment and implants must be considered in any future cost analysis. Proponents of robotic UKA propose that these costs may be partially offset by decreased length of hospital stay, reduced need for physiotherapy, fewer discharges to rehabilitation units or skilled nursing facilities, less opiate analgesia consumption and reduced readmission rates compared to conventional jig-based TKA.[33,39] Additional limitations of robotic UKA include extra incisions for the insertion of the femoral and tibial registration pins to enable optical motion-capture tracking. This may expose the patient to an increased risk of wound problems or infection. Accompanying CT scans with image-guided procedures are known to expose the patient to increased quantities of radiation. Overall time spent on the robotic procedure is also increased, with further time and resources required for preoperative segmenting and templating.[54]

Conclusion

Robotic UKA improves the accuracy of implant positioning, enhances postoperative functional rehabilitation, and may improve short-term functional outcomes in highly active individuals compared to conventional manual UKA. Robotic technology also provides live intraoperative data on knee kinematics through the arc of flexion that can be used to fine-tune implant positioning and optimize soft tissue tensioning. Robotic technology offers an avenue for low-volume UKA surgeons to achieve high levels of accuracy in implant positioning, which may help to improve implant survivorship and reduce the burden of revision disease. However, further studies are required to assess the effect of robotic UKA on long-term functional outcomes, implant survivorship, cost-effectiveness, and complications compared with conventional manual UKA.

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ICMJE CONFLICT OF INTEREST STATEMENT

FSH reports board membership of the *Bone and Joint Journal* and *The Annals of the Royal College of Surgeons*; consultancy for Smith & Nephew, Corin, MatOrtho and Stryker; payment for lectures including service on speakers' bureaus for Smith & Nephew and Stryker; royalties paid by Smith & Nephew, MatOrtho, Corin and Stryker, all outside the submitted work.
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