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(iv) Technology assisted unicompartmental knee replacement: results and functional outcomes

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Abstract
This review article focuses on the use of technology to assist implantation of Unicondylar Knee Replacements (UKR) for medial osteoarthritis of the knee. We provide the reader with an overview of the current published articles in peer reviewed journals investigating computer navigation, robotic-assisted surgery, patient-specific implants and instrumentation.

The literature on technology assisted UKR does show a trend towards less outliers and greater accuracy, in terms of implant positioning and restoration of mechanical axis. There is also a key role for technology to play in the training of future surgeons in technically demanding procedures such as UKR. However, long-term differences in patient outcome and implant survivorship have yet to be shown and further high quality studies are required with longer follow-up to demonstrate that any improvement in accuracy and consistency translates to improvements in actual patient outcomes.

Keywords computer navigation; patient-specific implants; patient-specific instruments; robotics; unicompartmental knee arthroplasty

Introduction
Technology assisted surgery is continually evolving and its role in trauma and orthopaedics appears to be gaining momentum. This is particularly apparent in total knee replacement (TKR), where there is a well-recognized relationship between accuracy of implant alignment and outcome. This review article focuses on the use of technology to assist implantation of Unicondylar Knee Replacements (UKR) for medial osteoarthritis of the knee.

Reported advantages of UKR include lower post-operative morbidity, quicker return to activities and a more normal feeling of the knee compared to TKR, which is most likely secondary to better restoration of knee kinematics without sacrificing ligaments, with some single-centre studies publishing UKR results better than those seen with TKR. These outcome studies, however, are not supported in terms of prosthesis survivorship by implant registry data from the United Kingdom, Australia, New Zealand, Norway, Sweden or Finland, which repeatedly report inferior midterm and long-term survivorship of UKRs compared with TKRs. This may be due to the fact that technically, UKR is a less forgiving operation, where both over- and under-correction of the coronal mechanical axis should be avoided, along with ensuring the sagittal tibial slope is not greater than 7°. It is widely accepted, that inserting a UKR accurately and in the optimal alignment will improve outcome. Certainly, inaccurate implantation is considered a factor for early failure.

We aim to provide the reader with an overview of current technology available to the orthopaedic surgeon to help aid UKR surgery, along with a review of current published studies where these methods have been applied.

Computer assisted navigation
In the last ten years, computer navigation in UKR has evolved as a tool to achieve the desired limb alignment and implant position. The type of navigation most commonly used is termed ‘image-free navigation’. Image-free TKR navigation systems have been modified to be used in UKR. The computer augments an already inbuilt anatomical model of the lower limb by surface registration. This is the process by which the surgeon uses a pointing device attached to a light-emitting diode (LED) to mark out predetermined points on the patient’s anatomy. The computer, via a camera positioned above the patient, registers the bony surfaces of the femur and tibia to be prepared and identifies their position in space. Using either the ‘gap balancing’ technique or the ‘measured resection’ technique, the surgeon receives real-time measurements for tibial and femoral bony cuts, to help both plan and then verify the cuts after they have been made. Real-time functional axes and kinematic analysis can be displayed on-demand at any point during surgery. The goal is to reproduce accurate implant positioning and precise reconstruction of the patient’s true mechanical axis regardless of pre-operative deformity.

The literature on computer navigated surgery in UKR is still limited. Most studies involve relatively small numbers, have a short-term follow-up and focus mainly on radiological parameters of alignment as opposed to patient reported outcome measures (PROMs). In addition to this, the type of UKR implant studied is often different, included within mixed groups in most studies, and the navigation software used is also not standard.

A recent meta-analysis by Weber et al. identified 10 studies meeting their entry criteria for imageless navigated UKR performed on living patients as opposed to knee models or cadavers. They looked at a pooled total of 258 navigated UKRs compared to 295 conventional non-navigated UKRs. Eight of the ten studies analysed the mechanical axis of the patients. They reported less outliers in the navigated group (11%) compared to the conventional group (30%). Six of the ten studies analysed radiological positioning of the femoral and tibial components, and found a
statistically significant reduced risk of outliers with the use of navigation. Only three of the studies reported on clinical results, with follow-up ranging from 18 to 36 months. Each study used a different clinical outcome measure, and while all reported an improvement in patient outcome scores in the short-term after surgery, there was no significant difference detected between the navigated and conventional groups. Three studies reported that the operating time was longer in the navigated group, with the mean increased time being 15.4 min. The main finding of all the above studies was that the use of navigation systems resulted in more accurate radiological parameters, including mechanical axis and implant position. The actual optimal position to place these implants is still unknown. Currently there are no studies reporting differences in clinical scores or implant survival at long-term follow-up with or without navigation in UKR. Any short- or medium-term studies they looked at in Weber et al.‘s meta-analysis showed no differences in these parameters between the two techniques.

Valenzuela et al.22 carried out a suitably powered retrospective case–control study comparing radiological post-operative mechanical axis restoration and implant position between 58 navigated UKRs and 71 conventional UKRs. The same cemented fixed-bearing UKR was used in all cases, though the patients were not randomly allocated into groups. Single long-leg stance radiographs were used to recreate physiological loading during gait. Navigation reduced the number of outliers and was slightly more accurate for implant positioning and coronal limb alignment, though this difference was not statistically significant. Interestingly, they reported a discrepancy between limb alignment measurement from the final intra-operative navigation system output and measurement from the post-operative long single leg stance radiographs of the same patients, which is something that has already been described in navigated TKR.21 Valenzuela et al. postulated that this may have been due to the effect of muscle forces applied during weight-bearing. They anecdotally reported that navigation appeared to improve the learning curve of residents performing arthroplasty, which has been mentioned in a number of the other studies.24

The study by Konyves et al.25 was one of the few that had medium-term follow-up, along with survivorship and clinical outcome measures of navigated UKR compared to conventional UKR. At an average of 6.9 years and 8.9 years for the 15 navigated UKRs and 15 conventional UKRs cases respectively, a higher proportion of navigated knees were well aligned when analysing both post-operative CT alignment views and weight-bearing long-leg radiographs, though this finding was not statistically significant. There was no difference in Oxford Knee Scores between the groups, though they reported that a larger proportion of malaligned knees had poor to fair Oxford Knee Scores. 3 out of 15 navigated UKR were revised to TKR for either persistent pain or disease progression, with a cumulative survival of 86.7% at 8 years using the Kaplan–Meier method. There was no statistically significant difference in survival between the navigated UKR and conventional UKR group. As with the other studies, the small number of cases meant statistical power was diminished. One significant confounding factor was that different implants were used in each group, which the authors did acknowledge.

The most recent study we found was by Manzotti et al.26 who conducted a retrospective case-matched study of 31 navigated UKRs vs 31 conventional UKRs. The same cemented, metal-backed fixed-bearing prosthesis was used in all cases. Clinical and radiographic outcomes were assessed at a minimum of 6 months. The study was not blinded or randomized. As with previous studies, the operating time was shorter in conventional UKR, and this was calculated to be statistically significant. There was no statistically significant difference between groups in the KSS and WOMAC scores at latest follow-up; however, the radiological parameters of mechanical axis, tibial slope and tibial component coronal alignment were significantly improved in the navigated group, and again there were less outliers seen with navigation.

In summary, computer assisted navigation overall improves accuracy of implant position and restoration of mechanical axis; however, data is awaited to see if this translates into any proven clinical advantage over conventional UKR. In addition, current systems have a limited ability to assess and guide optimal rotational alignment of the components. Navigation provides surgeons with real-time intra-operative feedback about implant position and limb alignment, which is particularly useful for this technically demanding procedure, in particular for surgeons in training. With the advent of dedicated software for UKR, accuracy and reproducible results should continue to improve (Figure 1).

**Robotic systems**

Robots are programmable machines that carry out a variety of tasks automatically or with minimal external impulse. Robot assisted surgery in orthopaedics began in the early 1990’s but the robots were challenging to operate and relatively invasive. More recently, novel robotic systems and concepts have been developed to improve the clinical efficacy of this technology in UKR. The two main types of robotic surgery systems are haptic or tactile systems, and autonomous systems.

**Haptic robotic systems**

Haptics is the science of applying touch (tactile) sensation and control to interact with computer applications. Haptic systems allow the surgeon to use or control the robot to perform the operation. These robotic devices are also called semi-active in distinction to active robotic assistive tools or autonomous robotic systems described in the next topic. The two main commercially
available tactile systems used in UKR are the Robotic Arm Interactive Orthopaedic System (RIO) (MAKO Surgical Corp, FL) and the Acrobot system (The Acrobot Company, London, UK).

The MAKO system utilizes 3D pre-operative CT scans to create a model of the patient’s knee. The surgeon uses this model to plan sizing and placement of the components pre-operatively. Intra-operatively, the surgeon will register the bony surfaces of the femur and tibia, allowing the computer to match the pre-operative CT model with the actual anatomy of the knee. Intra-operative kinematic data will also be collected to assess flexion and extension gaps, and an exact cutting zone for the robot will be created. The surgeon operates a tactile robotic arm attached to a high speed burr whilst viewing a 3D model of the knee. The robotic arm provides auditory and haptic feedback and the burr will automatically stop if attempts are made to resect too much bone or resect bone outside of the predetermined safe cutting zone.

Pearle et al. reported on their first clinical series of 10 robotic UKR using the MAKO system. The set-up time for the robot averaged 41 min, with an average of 7.5 min needed for the registration process. The average time for robot assisted burring was 34.8 min although this shortened after the first 5 cases. The mean tourniquet time was 67 min and the mean operation time was 132 min. Patients were followed-up to 6 weeks and the planned and subsequent intra-operative coronal tibiofemoral angles measured were all within 1°. Post-operative coronal alignment measured on long-leg radiographs was within 1.6° of the intra-operative measured values. They found the main initial benefits of this system were that it allowed accurate component position with minimal access, the burr allowed for creation of an individual press fit cavity, difficult to replicate with an oscillating saw, and unlike other commercially available robotic systems, rigid fixation of the robot to the patients anatomy was not required.

Lonner et al. conducted a pilot study prospectively comparing 27 conventional UKRs to 31 MAKO robotic arm assisted UKRs in matched cohorts. They measured the error of each technique by comparing the pre-operatively planned position for each tibial component with the post-operatively achieved coronal and sagittal alignment, using plain radiographs. Both onlay and inlay tibial components were included though the goals of alignment of each are different in the coronal plane, with inlay components implanted to match the patient’s anatomic tibia varus and onlay components placed 90° relative to the mechanical axis of the tibia. The variance in conventional UKR was 2.6 times greater than in robotic UKR, and there was a statistically significant increase in error in tibial component alignment with conventional UKR in the coronal and sagittal planes. The authors recognized that the plain radiographs they measured were not as reproducible as CT, in particular to match for limb rotation. They also did not measure femoral component position as this is difficult to determine on radiographs, and they did not look at overall limb alignment as long-leg radiographs were not utilized. Their findings were in agreement, however, with the cadaveric study by Citak et al. where CT was used pre- and post-operatively to compare accuracy of implant position between conventional UKRs and robotic UKRs using the MAKO system in 6 pairs of cadaveric knees.

In contrast, a more recent retrospective matched study by Hansen et al. compared 30 robot assisted MAKO UKRs to 32 conventional UKRs. They found the longer operative time in the robot assisted UKR group was statistically significant although there was no difference in blood loss, tourniquet time or intra-operative complications. Length of stay was shorter in the robot assisted UKR group. Full length coronal radiographs were analysed pre- and post-operatively and showed no differences in alignment of the tibial component or the coronal tibial axis. Medial tibial component overhang was significantly greater in the conventional UKR group, however. No short-term clinical differences were found at a minimum follow-up of 2 months.

Recently, Mofidi et al. reported on a series of 232 medial UKRs followed retrospectively to assess the accuracy of component placement using the MAKO system. They compared planned intra-operative robotic alignment with post-operative alignment on standardized radiographs and found 70% of prosthesis were inserted within 3° of where intended in the coronal and sagittal planes. Where there was malalignment of >5°, they attributed this to poor cementing technique as opposed to inaccurate bony cuts. They also felt radiological measurement of UKR prosthesis position is difficult without CT, a limitation they recognized with their study.

Cobb et al. published results from a prospective, randomized, double-blinded study comparing 13 minimally invasive robot assisted UKRs using the ACROBOT system to 14 conventional UKRs. CT was used pre- and post-operatively to assess the primary outcome measure of coronal tibiofemoral alignment. Secondary outcome measures were the American Knee Society Score (AKS) and the Western Ontario and McMaster Universities osteoarthritis index (WOMAC). Coronal tibiofemoral alignment fell within 2° of the planned pre-operative position in 100% of the robot assisted UKRs compared to only 40% of the conventional UKRs. At 18 weeks follow-up, the mean increase in AKS was twice as large in the robot assisted UKR group, and this was statistically significant. There was no statistically significant difference in WOMAC scores or operative time between the groups. The authors concluded the use of the Acrobot system resulted in fewer post-operative outliers compared with the control group. They also concluded, as with several of the authors from the studies mentioned above, that the introduction of robotic devices may shorten the learning period for surgeons in training acquiring a new technique as well as reducing the risk of error.

This was further investigated by Karia et al. who assessed the accuracy of UKR implant positioning by inexperienced surgeons performing both robotic-assisted and conventional UKR on dry bone models for the first time. They found surgeons were able to position components more accurately with the aid of the Sculptor RGA (formerly Acrobot). A 3D laser scanner was used to compare the planned position of the implants to the final position in all six degrees of freedom.

Besides these arm-controlled devices, a new generation of handheld robotic tools has emerged. The Navio PFS (Precision Freehand Sculptor) robot (Blue Belt Technology Pittsburgh, USA) combines CT-free navigation and semi-active robotic technologies (Figure 2). Based on similar concepts to those described in the navigation section, the surgeon collects intra-operative anatomical (single point(s) or surfaces) and kinematic landmarks using a pointer. No radiographs or scans are required pre-operatively, and only intra-operative data is used to build a
patient-specific frame of reference on which the computer system determines optimal options for implant positions and ligament balancing. Four phases are necessary during surgery; the set-up phase consists of placing separate femoral and tibial trackers to be used as Digital Based Reference (DBR). The registration phase is similar to other image-free technology systems. This stage is crucial as it allows the surgeon to collect relevant anatomical landmarks and assess the soft tissue envelope and tension by stressing the knee in valgus and flexion to assess real-time changes in coronal alignment. The computer system collects all this data and displays a series of graphical interfaces for the implant planning phase. Using a sterile touch screen, the surgeon can modify femoral and tibial component positions and orientation in all directions. Once the surgeon is satisfied with the component position, gap balancing and implant surface contacts, the execution phase remains. A lightweight handheld robotic tool is calibrated and used to execute the plan. This device is comparable to an orthopaedic arthroscopic knee shaver and is tracked by an optical tracking camera via a reflective sphere that is affixed to it. At the tip of the tool is a 5 or 6 mm Burr centred inside a metallic sleeve. Three different modalities of bone resection are possible with this burr: autonomous, speed controlled or manual. The autonomous modality enables the surgeon to resect bone automatically as the burr activates in the planned bony resection area. The spherical burr retracts into its sleeve if the surgeon moves the tool away from the safe zone. Speed control means burr speed varies depending on the location of the cutting tool. The burr runs at high speed where the bone is planned to be removed, medium speed in critical areas and no speed at all area outside of the planned bony bed for the implant. The manual modality allows only the surgeon to be in total control of the burr using a foot pedal whilst receiving visual feedback on a monitor. Progress of bone resection is displayed by means of a coloured code graphical interface, similar to a geographical contour map, each colour representing different layers of depth in the implant’s bone bed. Once bone resection is complete, the implant is trailed to verify alignment and knee kinematics, with immediate computer feedback. This system is CE and FDA approved and has already been assessed independently with reported errors between ‘planned’ and ‘achieved’ implant placement being comparable to results of other systems on the market. The RMS errors reported between the ‘planned’ and ‘actual’ implant placement were up to 2.5° and 1.5 mm.33,34 This system combines navigation with a precision cutting tool to prepare the bone surface.

**Autonomous robotic systems**

Autonomous robotic systems, or active robots, offer an alternative to haptic systems, and this is where the robot completes the case independently whilst the surgeon monitors its progress. Their use in orthopaedic surgery is still under investigation. Initially the ROBODOC (Curexo Technology Corporation, California) was used in the early 1990’s, but its popularity declined secondary to safety concerns.35

More recently, novel hybrid semi-autonomous robotic systems have become available and are gaining popularity. The mini bone-attached robotic system (MBARS) robot and Praxiteles systems mount onto the femur and complete bone resection during TKR.16,37 Naturally, further development and testing are needed to assess the efficacy of these small bone-mounted robots.

**Patient-specific instrumentation and patient-specific implants in UKR**

Patient-Specific Instrumentation (PSI) was introduced to allow customized bone cutting, with the aim of improving accuracy, minimizing the number of instruments required, reducing surgery time and reducing overall costs. PSI requires greater pre-operative surgical planning and is based on anatomical data from computerized tomography (CT) scans or magnetic resonance imaging (MRI). Customized disposable cutting blocks are created, specific for each patient’s anatomy. These blocks fit accurately on the femoral and tibial surfaces and are expected to achieve better cut alignment when compared to conventional cutting jigs.

With Patient-Specific Implants (PSIM), both the cutting blocks and the implants are specifically designed for each individual patient. The same pre-operative imaging is used to manufacture the cutting blocks and the custom implants, based on native femoral and tibial bone characteristics.

Several studies have shown the importance of achieving optimum implant alignment, with varus/valgus and tibial slope malpositioning being a risk factor for polyethylene wear and UKR implant failure.16,35,39 Though published reports on patient-specific instrumentation and implants in TKR are increasing in number, there is still a relative paucity of articles on patient-specific instrumentation and implants in UKR.

In 2010, Koeck et al.35 studied the implant position and leg axis correction of 32 patient-specific medial UKAs by use of standardized radiographs and CT. The authors used both patient-specific guides and patient-specific implants. They demonstrated that with patient-specific instrumentation and implants, a statistically significant improvement in mechanical limb alignment, component positioning, orientation and coverage was achieved, with excellent accuracy and consistency. This study, however, did not have a control group to compare with conventional implants and instruments.

In 2013, Trong et al.40 investigated the tibial component alignment of 28 medial UKAs implanted using patient-specific cutting blocks. CT analysis of implant positioning showed a high accuracy of coronal tibial implant position (0.3° ± 1.7°), posterior slope (1.1° ± 2.6°) and external rotation (1.5° ± 3.3°). There was no control group in this study, and the femoral component was not assessed, although the authors did note this, explaining that for this implant, femoral component orientation is based on the tibial cut.
Kerens et al. compared radiographic positioning of implants in 30 conventional Oxford UKA compared with 30 Patient Specific Guided (PSG) Oxford UKA. They found no statistically or clinically significantly differences between the two groups, except for the positioning of the femoral component in the frontal plane. Their results did, however, demonstrate smaller ranges and standard deviations in implant position in the PSG group. Radiographic evaluation was based on knee radiographs, and therefore the mechanical and anatomical axis of the tibia and femur was approximated. Component rotation could not be evaluated for this same reason. These results represent the first 30 PSG Oxford UKA performed by a single surgeon in this institution, who was well experienced in conventional Oxford UKA. The results may therefore have been different if both techniques were compared at the same stage of the surgeon’s learning curve.

Carpenter et al. studied morphometric data (virtual surgery) in 30 knees (20 medial and 10 lateral UKRs) to compare size, match and fit between patient-specific implants and off-the-shelf implants from various manufacturers. All implants were modelled in computer aided design (CAD), and the patient-specific implants utilized the CAD designs that were generated during the implant manufacturing process. Statistically significant reductions in the average amounts of both overhang and under-coverage of the tibia in both medial and lateral UKRs were seen with the patient-specific implants vs the off-the-shelf designs. The PSI also provided significantly greater tibial cortical rim surface area coverage, compared to incrementally sized off-the-shelf implants. However, the virtual nature of this study removes many other variables that may affect choice of implant size, such as matching the femoral component to the tibial component, visualization of the tibial surfaces and soft tissue constraints. Thus it has not been confirmed whether these results are consistently reproducible in vivo.

Conclusion

The aim of technology in arthroplasty is to improve accuracy and consistency, with the hope of increasing longevity and survivorship of implants and giving improved functional outcomes. UKR is a more technically challenging operation compared to TKR, and controversy exists as to whether UKR is comparable to TKR in terms of patient satisfaction rates and survivorship. We believe that surgical precision and accuracy will have a positive influence on clinical outcomes, although it is not known how much precision or accuracy is actually required in UKR to achieve clinically satisfactory results.

Navigation allows the surgeon to assess real-time cut placement, implant positioning and knee kinematics. The literature on navigated arthroplasty does show a trend towards less outliers and greater accuracy, in terms of implant positioning. Partly due to the recent introduction of such technology and also the limited number of surgeons/centres performing navigated UKR’s, long-term data will not be available for some years yet.

The available literature on robotics and patient-specific guides and implants is more limited, demonstrating levels of evidence in categories III, IV and V, and involving only small numbers of patients.

Understandably, few centres across the world will have access to this technology, as it is relatively new and there can be financial barriers to using some of these systems; in particular robots, which have high start-up costs as well as the need for continuous upgrades and calibration.

Further study is required to assess the long-term implications of the use of this technology in UKR; however, embrace of such technology is needed in order to make the first steps towards this goal of improving function with technology assistance.

REFERENCES


