Robotic Total Knee Arthroplasty: Surgical Assistant for a Customized Normal Kinematic Knee

KENNETH L. URISH, MD, PHD; MICHAEL CONDITT, PHD; MARTIN ROCHE, MD; HARRY E. RUBASH, MD

abstract

Although current total knee arthroplasty (TKA) is considered a highly successful surgical procedure, patients undergoing TKA can still experience substantial functional impairment and increased revision rates as compared with those undergoing total hip arthroplasty. Robotic-assisted surgery has been available clinically for almost 15 years and was developed, in part, to address these concerns. Robotic-assisted surgery aims to improve TKA by enhancing the surgeon’s ability to optimize soft tissue balancing, reproduce alignment, and restore normal knee kinematics. Current systems include a robotic arm with a variety of different navigation systems with active, semi-active, or passive control. Semi-active systems have become the dominant strategy, providing a haptic window through which the surgeon consistently prepares a TKA based on preoperative planning. A review of previous designs and clinical studies demonstrates that these robotic systems decrease variability and increase precision, primarily with the mechanical axis and restoration of the joint line. Future design objectives include precise planning and consistent intraoperative execution. Preoperative planning, intraoperative sensors, augmenting surgical instrumentation, and biomimetic surfaces will be used to re-create the 4-bar linkage system in the knee. Implants will be placed so that the knee functions with a medial pivot, lateral rollback, screw home mechanism, and patellar femoral tracking. Soft tissue balancing will become more than equalizing the flexion and extension gaps and will match the kinematics to a normal knee. Together, coupled with advanced knee designs, they may be the key to a patient stating, “My knee feels like my natural knee.” [Orthopedics. 2016; 39(5):e822-e827.]

Total knee arthroplasty (TKA) is a common and successful treatment for end-stage osteoarthritis. There are more than 600,000 primary TKAs performed annually, with a growth rate of 10% annually.1,2 In the Medicare population, approximately 250,000 primary TKAs are performed each year, with overall volume increasing 160% during the past 20 years.3

The main goals of TKA are aimed at relieving pain, improving the patient’s quality of life, and restoring function while optimizing implant longevity. Multiple studies have demonstrated that TKA provides pain relief and improved quality of life.4-6 These improvements in functional outcomes remain more than 20 years after the index procedure.6 For the enormous benefit, the procedure remains cost effective, delivering consistent, reproducible, and reliable results.7

Although TKA is considered a highly successful surgical procedure, the results are inferior when compared with total hip
arthroplasty (THA). Total knee arthroplasty has been associated with a higher incidence of persistent postoperative pain than THA.\textsuperscript{8-10} Patient satisfaction following TKA ranges from 75% to 89% using a variety of patient-reported outcome measures.\textsuperscript{11-15} Patients undergoing TKA still experience substantial functional impairment.\textsuperscript{14} More than half of all patients undergoing TKA report some degree of limitation in normal activities of daily living,\textsuperscript{14} and the absence of functional impairment is an important predictor of overall satisfaction.\textsuperscript{12} Patient demographics do not explain these differences.\textsuperscript{10,15} Although appropriate expectations are important, functional impairment secondary to biomechanical deficiencies of TKA implants severely limit TKA outcomes.\textsuperscript{15} Total knee arthroplasty implants do not consistently reproduce the kinematic patterns of a normal knee.\textsuperscript{16-18} In particular, patients undergoing TKA have significantly less axial rotation during normal gait and activities of daily living.\textsuperscript{16,19}

Several factors, including surgical technique, polyethylene wear, loosening, preoperative comorbidities, and pain levels, have been shown to be associated with failure after TKA.\textsuperscript{20} Surgical technique has been reported to be the most common cause for failure in TKA.\textsuperscript{21} Initial interest in computer navigation and robotic systems involved improving known variables that had been demonstrated to limit TKA results, including mechanical axis, joint-line alteration, and surgeon variability. These were the initial motivations that robotic TKA attempted to address. They are still challenging to obtain.

**History of Robotic Total Knee Arthroplasty**

Robotic systems combined with navigation were initially developed to improve the clinical outcomes and reproducibility of TKA. These different approaches have been classified into 3 main categories: passive, active, and semi-active robotic systems.\textsuperscript{2,22} Passive systems complete a portion of the procedure under continuous and direct control of the surgeon. Active systems perform a task independent of any surgeon involvement. Semi-active systems provide feedback that augments the surgeon’s control of the tool, typically with tactile feedback. These systems are also known as *haptic*. Initial robotic systems involved either passive or semi-active systems that restricted motion for the cutting tools. Only a limited number of systems have been introduced into the clinical setting.

Autonomous systems complete a surgical task independent of the surgeon, with no assistance. Early designs have been around for a number of years. These include the ROBODOC (Curexo Technology, Fremont, California) and CASPAR (URS Ortho, Rastatt, Germany). ROBODOC was the first robot used clinically in orthopedic surgery. Initial clinical trials began in 1994, and it was approved by the US Food and Drug Administration in 2008.\textsuperscript{23} Its clinical success and usefulness have been demonstrated in a series of clinical trials.\textsuperscript{24-27} In 2 different prospective studies comparing ROBODOC-assisted TKA with manual TKA, the robot had more accuracy and less variation in the mechanical axis, took an additional 25 minutes, and resulted in no difference in patient-reported outcome measures.\textsuperscript{28,29} Initial concerns and limitations focused on aborted surgeries and increased operative time, after early clinical reports noted technical complications in approximately 10% of cases.\textsuperscript{28,31}

CASPAR was another early autonomous system. Initial results focused on improving consistency and decreasing variability in the mechanical axis of the leg. Many studies have demonstrated the importance of the mechanical axis in TKA function, outcomes, and longevity.\textsuperscript{32,33} Early clinical reports of this device noted improved tibiofemoral alignment within 1°,\textsuperscript{25,27} as compared with 2.6° in the manual-operated historical control group. In initial reports, no adverse results were reported.\textsuperscript{23} Intraoperative orientation of the robot was restrictive in that femoral and tibial bicortical bone screws had to be placed preoperatively as fiducial markers for registration of the preoperative computed tomography (CT) scan with intraoperative robotic function.\textsuperscript{27}

The Robotic Arm Interactive Orthopedic System (RIO; MAKO Stryker, Fort Lauderdale, Florida) is a haptic system available in clinical practice for unicompartmental knee arthroplasty. Preoperative CT is used in surgical planning to help determine component sizing, positioning, and bone resection; this is confirmed and adjusted intraoperatively based on the patient’s specific kinematics prior to any surgical resection. Intraoperatively, the robotic system provides haptic feedback to prevent bone resection outside of the executed template.\textsuperscript{34} Retrospective review of a case series demonstrated extreme precision with almost no radiographic outliers.\textsuperscript{35} A series of feasibility studies demonstrated that, as compared with manual techniques, the robotic system has increased accuracy in re-creating the posterior tibial slope and coronal tibial alignment.\textsuperscript{35,37} Unicompartmental knee arthroplasty has a history of being a demanding surgical procedure with a steep learning curve. The addition of a robotic system significantly decreases this learning curve.\textsuperscript{37-39}

**Current Design Goals**

The current motivation behind robotic-assisted TKA is improving surgical precision, advancing articular surface design that allows for independent intercompartmental resurfacing, optimizing component positioning based on normal soft tissue function, and ultimately improving patient outcomes. Robotic-assisted surgery has the potential to achieve these goals by enhancing the surgeon’s ability to generate reproducible techniques through an individualized approach. Anatomic restoration with optimized soft tissue balancing, reproducible alignment, and restoration of normal knee kinematics are demonstrated advantages of robotic-
assisted partial knee surgery.\textsuperscript{40-43} The clinical benefit from the improved precision afforded by robot-assisted TKA remains a topic of controversy.\textsuperscript{44,45}

**Mechanical Axis**

The importance of mechanical axis alignment in implant longevity has been well documented.\textsuperscript{33,46,47} This is a surgical variable that has been reported to have significant variation. Mechanical axis variation of greater than 5\textdegree in more than 30\% of patients has been documented in some series.\textsuperscript{33} Studies from the Mayo registry have demonstrated that a mechanical axis within 3° of a neutral alignment did not improve 15-year survival. There was a significant loss of implant longevity when implants fell outside of this range.\textsuperscript{28}

A series of studies have used this range as a benchmark for describing outliers to demonstrate that current robotic TKA techniques decrease surgical variation. Initial reports of robotic-assisted TKA used this as one of the primary endpoints to show increased reproducibility.\textsuperscript{27} Other studies have demonstrated no mechanical axis outliers with robotic-assisted surgery, whereas control groups had approximately 20\% outliers.\textsuperscript{41} Despite multiple studies demonstrating improved alignment and intraoperative benefit, the clinical impact remains less clear.\textsuperscript{49}

Robotically-assisted techniques have been used to compare the outcomes of the 2 approaches to mechanical axis coronal tibial and femoral cuts. Standard surgical technique for the overall alignment of the TKA, which includes making the tibial and femoral cuts perpendicular to the mechanical axis, was first reported by Insall et al.\textsuperscript{50} Other approaches include a more anatomic approach, keeping the tibial coronal cut in varus and the femoral cut in a symmetrical valgus to create a neutral mechanical axis.\textsuperscript{51,53} A robotic-assistive device was used in a prospective, randomized study of more than 100 patients comparing outcomes between these 2 approaches. There was no difference in measures of varus-valgus laxity, Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score, range of motion, and Harris Hip Score.\textsuperscript{54}

**Joint-Line Alteration**

Alteration of the joint line more than 5 mm has been associated with poor outcomes, including patella baja, patella button impingement, and anterior knee pain. Other studies have noted that joint-line alteration can lead to mid-flexion instability.\textsuperscript{55}

There have been limited studies focusing on joint-line accuracy. In a prospective study on 60 patients in a single institution, the ROBODOC had 3\% joint line outliers (>5 mm), compared with 21\% using conventional techniques.\textsuperscript{41} In a larger prospective cohort of 206 patients, a patient navigation system (Brain Lab) showed no differences in joint-line shift compared with traditional techniques. Outliers were defined as greater than 8 mm, which included less than 7\% of patients in both groups.\textsuperscript{56}

**Operative Time**

The focus on decreasing variability and increasing precision has introduced the liability of increased operative time. Based on some initial difficulties with the ROBODOC, studies have focused on this system. In a series by Chun et al,\textsuperscript{23} based on simple criteria for an aborted TKA, including when the expected time would exceed 30 minutes to recover from an error, when there were 4 repetitive failures on a step that could not be skipped, or when soft tissue was in danger of being damaged, the aborted procedure rate was 22\%. The most common errors occurred after the milling procedure began, were secondary to interactive factors, and were when the patellar tendon was in danger of being damaged.\textsuperscript{23} There is a wide range of aborted procedures, with other studies reporting less than 5\%.\textsuperscript{41} Regardless of the percentage of aborted procedures, increased operative time is a known risk factor for periprosthetic joint infection.\textsuperscript{57} This remains a detriment to robotic-assisted procedures given the potential for patient harm.

**Future Innovations in Robotic-Assisted Total Knee Arthroplasty**

Current design has focused on decreasing outliers and improving accuracy in TKA radiographic outcomes. Future design innovations will focus on creating a biomimetic implant that will reproduce the kinematics of a normal knee. These innovations will be implemented in a way that simplifies the process and minimizes the learning curve. It is difficult to predict the array of technological innovations that will be used to transform robotic-assisted TKA. Critical areas include preoperative analysis, intraoperative sensors, and robotically controlled instrumentation.

Preoperative planning with current robotic technology typically involves some type of imaging modality, such as CT or radiographs, for registration of anatomic landmarks into the robotic registered space to define boundaries and the operative plan. The next step is to go beyond imaging to appreciate the kinematics of the operative knee before being altered by the pathology of arthritis. The preoperative plan will be used to re-create the desired anatomic and kinematic framework.

Robotically controlled devices will augment current cutting devices and instrumentation to position the implant according to the preoperative plan. Navigation serves a critical role in the ability of the robot to register its position in space. Traditional navigation techniques rely on CT scans, fluoroscopy, and mechanical point picking to define the anatomy. Tracking and guidance of instruments is based on cumbersome optical and electromagnetic devices. Development of new devices, such as navigation-free bone cutting, has the potential to eliminate the need for implant-specific instrumentation along with the traditional navigation equipment required.\textsuperscript{58}
Intraoperative sensors will be essential for surgical implementation of the preoperative plan. Measurement of forces and contact points across the joints and implants through range of motion will quantify the current attempts to perform soft tissue balancing by feel. The surgeon will be given real-time feedback to improve bone cuts, soft tissue tension, and ligamentous balancing to obtain the perfect outcome. The concept of “trialing” the knee will be redefined. Instead of verifying that the components are sized correctly, the re-creation of knee kinematics will be assessed. These changes will be implemented using robotically controlled devices where haptics will provide unique feedback so that the robotic device assists the surgeon. There are already multiple sensor types under development.59-61

Tactile or haptic feedback has become a major innovation in robotic surgery. Computer-assisted navigation uses registration from predefined landmarks to identify where components are placed in space. Haptics allow these predefined boundaries from navigation technology to allow the robot to become a surgical assistant instead of the surgeon. Instead of an autonomous system where the robot is in control of the cuts with no dynamic assistance from the surgeon, the robot provides resistance when the surgeon attempts to deviate from the preoperative plan.62 A challenge in haptic feedback surgery includes keeping the feedback stable and transparent.63 The use of haptics allows precision with efficiency and accuracy. Intraoperative sensors will quantify forces across the joint to verify restoration of normal kinematics. The dynamics of trialing components will be redefined with real time in vivo measurements that will allow kinetic optimization through refinements of bony cuts and soft tissue balancing. Robotics allow precise intraoperative adjustments based on an optimized kinematic profile of the individual patient’s knee.

Biomimetic surfaces will become critical pieces of the implant where the TKA will mimic the motion of a native knee.64,65 This will require an understanding of the normal subset of patients with normal knee kinematics. Complex geometries of articular surfaces will be required that will be able to re-create the kinematics to match the normal kinematic subset. Passive intraoperative kinematics will be matched to postoperative kinematics that are designed to mimic a normal knee subset. The ultimate goal of these surfaces is to re-create the 4-bar linkage system in the knee to get these ligaments to work vs driving the ligaments. Implants will be placed so that the knee functions with a medial pivot, lateral rollback, screw home mechanism, and patellar femoral tracking. Soft tissue balancing will become more than equalizing the flexion and extension gaps and will match the kinematics to a normal knee. This may be in reference to the contralateral knee or a library of native knees.

**Conclusion**

To date, robotic-assisted TKA has improved consistency and decreased variability at the cost of increased operative times with no clear evidence supporting improved clinical outcomes. In the future, robotic-assisted TKA has the potential to become a valuable tool to assist the surgeon in optimizing the patient-specific implantation of innovative implants, which will be designed to fit the knee, instead of the current design philosophy of having the knee fit the implant. This has the possibility to ultimately improve patient outcomes with a knee that feels identical to the previous healthy, native knee.

**References**


