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Available Robotic Platforms in Partial and Total Knee Arthroplasty

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Knee arthroplasty typically relieves pain and restores function, but dissatisfaction and early revision occur at a frequency that places a significant burden on patients and the health care system. A new generation of computer and robotic systems has been developed to help orthopaedic surgeons enhance precision and accuracy, with the hope of making outcomes more reliable. Surgical robots can be active, semiactive, or passive. Each level of robot autonomy vs surgeon control has potential benefits and limitations. Currently available robotic platforms are discussed in the context of historical developments, published outcomes, and future directions.

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Introduction

Joint replacement arthroplasty is one of the most effective surgical developments of the last century. Arthroplasty surgeons relieve pain and to restore mobility to arthritic patients who previously would have experienced profound disability. With an aging population, demand for knee arthroplasty has grown exponentially,[1] potentially outstripping the supply of fellowship-trained surgeons. This demand is further driven by a broadening of indications to include younger and more active patients.[2] Patients now elect knee replacement in the hopes of returning to active lifestyles and expecting decades of durability. Unfortunately, imperfect outcomes have not been eliminated, and catastrophic failures still occur. Despite more than 40 years of innovation, most reported rates of satisfaction after total knee arthroplasty remain less than 90%,[3-6] and despite the excellent survivorship reported in many series for partial,[5,7,8] and total knee arthroplasty,[9-12] 28.8% of patellofemoral arthroplasties, 18.0% of unicondylar knee arthroplasties, and 6.5% of total knee arthroplasties are revised within 12 years according to the most recent Australian registry data.[13]

Improvements in metallurgy, polyethylene, manufacturing, and component design have created the opportunity for greater implant longevity, and possibly improved function. Nonetheless, fixation, alignment, and ligament balance continue to drive surgical outcomes—affecting not only survival[14] but function and pain relief. Implant choice matters; registry data show varied revision rates by prosthesis brand and design (range: 3.0%-11.9% at 12-year follow-up), with factors such as bearing type (fixed vs mobile), level of constraint (cruciate retaining vs posterior stabilized), fixation (with or without cement), patella resurfacing, and type of polyethylene statistically associated with survivorship.[13] Nevertheless, implant "improvements" have not led to significantly improved rates of patient satisfaction,[6] implying that improvements in surgical technique may be required to improve outcomes. Surgery has traditionally been as much an art as a science; this has certainly been the case with ligament balancing in knee replacement. Apprentice surgeons learn from experienced masters "how tight is tight, and how loose is loose," to borrow a phrase from Chitranjan S. Ranawat. This craftsmanship is understandably prized, but subjectivity must be removed for outcomes to improve. Recent innovations have attempted to improve the reliability of partial and total knee arthroplasty. Standard manual surgical instruments are continuously being refined and custom instrumentation has been developed, but major improvements in surgical accuracy and precision may require more groundbreaking innovation. Computer guidance and robotic assistance have been championed to offer such a promise.

The value of computer assistance in knee arthroplasty relates to the ability of the platform to set optimal goals for implant

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position (relative to bone anatomy, limb alignment, and soft tissue tension), to accurately orient the surgeon with reference to these goals, and to enable precise bone preparation, soft tissue releases or both—leading to a result that reproduces the surgical plan, without meaningfully increasing surgical time or complexity. The optimal tool would also reduce trauma to the surrounding bone and soft tissues, thereby minimizing surgical complications. Robotic bone preparation may also allow the design of implants that could not realistically be implanted manually, freeing implant engineers to consider a broader range of geometries and design concepts that could preserve ligaments, conserve bone, and improve fixation, kinematics, load transfer, or other features of the prosthetic joint that can affect patient outcomes.

Robot-assisted orthopaedic surgical platforms have been classified as active (ie, robot autonomously performs portions of the operation planned by the surgeon), passive (ie, robot positions a cutting guide at a computer-navigated position but does not perform surgical manipulation of the patient and does not constrain the surgeon), or semiactive (robot augments the surgeon's ability to control resections by guiding and physically constraining the surgeon within a 3-dimensional (3D) space but does not autonomously perform bone resection).[15] This review discusses all 3 classes of surgical robot, while not discussing computer navigation in detail. We acknowledge that the distinction between some passive robots and computer navigation is somewhat arbitrary, as any technology reliant on human manipulation of a handheld power saw remains vulnerable to technique-related deviations from the planned bone resection that may affect precision[16] or cause iatrogenic injury.

History of Robotics in Knee Arthroplasty

Robotic tools to increase surgical precision and accuracy have been in development and investigated since the 1980s. The first to see clinical use in joint replacement was ROBODOC (THINK Surgical Inc, Fremont, CA), originally developed by the IBM T.J.Watson Research Center (Yorktown Heights, NY) in collaboration with the University of California, Davis. It was introduced clinically for total hip replacement in 1992 at Sutter General Hospital (Sacramento, CA), but most of the early clinical experience with ROBODOC was in Germany. The orthopaedic surgeon performed the surgical exposure and planned the implant position, but the robot autonomously machined the femoral canal with a bone milling device. Improvements in implant fit and fill were achieved at the expense of increased surgical time and blood loss.[17] Although some surgeons noted fewer intraoperative femoral fractures compared with conventional techniques,[17] others did not, and technical complications related to use of ROBODOC were reported in 9.3% of cases,[18] along with increased dislocation rates attributed to abductor and other soft tissue injuries.[19]

ROBODOC was applied to total knee arthroplasty by German surgeons in March 2000. The system initially necessitated that titanium fiduciary markers be surgically implanted in the patient before a computed tomography (CT) scan. Femoral and tibial mechanical axes were defined relative to fiduciary pin position, and the surgery was planned on 3D planning software. After standard surgical exposure, the limb was immobilized in flexion and distracted with additional fixation pins. The robot was fixed to the patient and allowed to make bone cuts without further surgeon interaction. A study of the first 100 cases revealed that planned alignment was achieved within 3° without exception, but conversion to conventional manual technique was required in 5% of cases.[20] Typical surgical duration was increased during the learning curve, but improved to an average of 90 minutes with experience. Clinical outcomes and complications were not reported, but the authors continued to use the robot, accumulating 500 ROBODOC total knee arthroplasties (TKAs) by 2002. Fiduciary markers were eventually replaced with an anatomical registration process, matching points registered on the bone surface to a 3D surface model developed from the preoperative CT scan.[21] This did not eliminate the need to fixate the bones with pins during TKA, but did eliminate the need for an additional procedure. Shortly thereafter, questions arose regarding the safety of ROBODOC that coincided with a rise in litigation.[22] Use of ROBODOC in Germany plummeted even though the complications noted in hip replacement may have been related to surgical technique or planning,[19] rather than a failure of the robot to precisely execute the surgical plan.

Interest in ROBODOC continued in Asia, and the system underwent changes in milling speed and cutting paths to reduce robot invasiveness and decrease milling time.[17] A randomized controlled trial (RCT) of the ROBODOC TKA procedure without fiduciary markers demonstrated greater precision than manual surgery, but no difference in Knee Society Scores or range of motion.[23] Soft tissue complications including patellar tendon rupture and peroneal nerve injury occurred with attempts to use minimally invasive exposures in early robotic cases, because of trauma from the high-speed cutter. No further soft tissue complications occurred after the surgeons switched to wider surgical exposures and smaller fixation pins. In a subsequent RCT of 30 patients undergoing bilateral TKA, postoperative CT scans showed less than 3° of deviation from neutral coronal alignment in 100% of the robotic knees but only 76.7% of conventional knees.[24] Clinical outcomes were comparable at 1 year, but postoperative drainage was lower in the robotic surgery group, and there was no increase in soft tissue complications. A larger RCT again demonstrated improved precision with ROBODOC, resulting in no alignment outliers greater than 3°. ROBODOC was associated with fewer cases of flexion-extension gap imbalance, less suboptimal posterior cruciate ligament (PCL) tensioning, less postoperative drainage, and comparable perioperative complications. ROBODOC cases, however, took an average of 25 minutes longer to perform. There were no relevant differences with respect to range-of-motion, WOMAC, and HSS knee scores over 3-year follow-up.[25]