Robotic systems in orthopaedic surgery

Robots have been used in surgery since the late 1980s. Orthopaedic surgery began to incorporate robotic technology in 1992, with the introduction of ROBODOC, for the planning and performance of total hip replacement. The use of robotic systems has subsequently increased, with promising short-term radiological outcomes when compared with traditional orthopaedic procedures. Robotic systems can be classified into two categories: autonomous and haptic (or surgeon-guided). Passive surgery systems, which represent a third type of technology, have also been adopted recently by orthopaedic surgeons.

While autonomous systems have fallen out of favour, tactile systems with technological improvements have become widely used. Specifically, the use of tactile and passive robotic systems in unicompartmental knee replacement (UKR) has addressed some of the historical mechanisms of failure of non-robotic UKR. These systems assist with increasing the accuracy of the alignment of the components and produce more consistent ligament balance. Short-term improvements in clinical and radiological outcomes have increased the popularity of robot-assisted UKR.

Robot-assisted orthopaedic surgery has the potential for improving surgical outcomes. We discuss the different types of robotic systems available for use in orthopaedics and consider the indication, contraindications and limitations of these technologies.

The term ‘robot’ is derived from the Polish word robota meaning forced labour, and describes a machine that carries out a variety of tasks automatically or with a minimum of external impulse, especially one that is programmable.¹

There are two main types of robotic surgery systems: haptic and autonomous. Haptic or tactile systems allow the surgeon to use or ‘drive’ the robot to perform the operation. This technology requires constant input by the surgeon for the procedure to proceed. In contrast, autonomous robotic systems require the surgeon to perform the approach and set up the machine, but once engaged, the robot completes the surgery without the surgeon’s help.² The use of robotic technology has, in some cases, facilitated minimally invasive surgery,² which has gained popularity with some patients. In spinal surgery, robotics have been successfully used to increase the accuracy of placement of implants.³ Furthermore, robotic technology can improve the radiological alignment of implants,⁴ as predicted by the pre-operative plan.

Haptic robotic systems

The Robotic Arm Interactive Orthopedic System (RIO) (MAKO Surgical Corp., Fort Lauderdale, Florida) is an example of a commercially available, tactile robotic system that requires active participation of the surgeon to complete a unicompartmental knee replacement (UKR). It uses pre-operative CT scans to create a three-dimensional (3D) computerised model of the patient’s knee. The surgeon uses this model pre-operatively to plan the sizing and placement of the components. Intra-operatively, the surgeon will reference the bony surfaces of the femur and tibia, allowing the pre-operative model to be ‘merged’ with the actual anatomy of the knee. After taking the knee through a range of movement, the flexion-extension gaps can be assessed and the operative plan finalised in terms of component placement, creating an exact cutting zone for the robot. The system’s algorithm relies heavily on the pre-operative planning or templating process. During the resection of bone, the surgeon views the 3D model of the knee on a monitor while manipulating the burr. The robotic arm provides auditory as well as haptic feedback, limiting the force-controlled tip of the rotating burr to resect bone only within the confines of the pre-defined cutting zone. An additional safety feature automatically stops the burr if the surgeon goes outside the pre-determined zone. This feature also engages if
the computer determines that the surgeon is resecting more bone than necessary. These robotic features monitor the operation and provide the intra-operative data necessary for the preservation of bone stock and accurate placement of the components, both of which are thought to improve the outcome after UKR. The RIO system allows the surgeon to execute the pre-operative plan with great precision. However, if this plan is flawed, the system cannot compensate for it.

In 2010, Roche, Augustin and Conditt reviewed 43 cases of RIO assisted UKR and showed that 344 radiological measurements were made with only three abnormal radiological findings. They concluded that UKR using this system showed promising initial results. The RIO robot-controlled arm allows the surgeon to operate through a much smaller incision, which has been associated with a shorter recovery and rehabilitation time. Typically, robot-assisted UKR is performed as an outpatient procedure; however certain patients may require a 24-hour hospital stay.

Despite the technical demands and stringent tolerances required for UKR, the RIO system has quite a short learning curve, particularly for less experienced surgeons. The system has safety features that monitor the procedure to ensure that the pre-operative plan is executed. In 2009, Coon reported on the learning curve, showing that the operation initially took between 80 and 120 minutes, decreasing to about 40 minutes after 20 cases.

The Acrobot system (The Acrobot Company, London, United Kingdom) is another tactile system which shares many features with the RIO system. Both use pre-operative CT scans to build a model of the patient's knee, which is either verified or modified after an intraoperative registration process. It comprises a surgeon-operated, high-speed cutting apparatus attached to a robotic arm with which, as with RIO, bone resection is constrained to a predetermined zone based on the pre-operative plan.

Cobb et al. published results from a prospective, randomised trial of minimally invasive Acrobot-assisted UKR versus UKR performed without robotic assistance. The primary outcome measure was radiological differences in the planned and achieved tibiofemoral angles, and secondary outcome measures included the American Knee Society score (AKS) and the Western Ontario and McMaster Universities osteoarthritis index (WOMAC). The mean pre-operative AKS score for the Acrobot group was 97.3 and for the conventional surgery group was 104.9, representing a 7.6 point pre-operative difference between groups at baseline. The post-operative AKS scores increased by a mean of 65.2 points in the Acrobot group and a mean of 32.5 points in the conventional surgery group; a difference of 31.7 points. The Acrobot-assisted group required a mean 16 minutes of additional operative time when compared with the traditional surgical group. For all of the Acrobot-assisted group, the tibiofemoral alignment of the knees fell within 2° of the planned pre-operative position. In contrast, only 40% of the conventional surgery group achieved this. Thus, the authors concluded that the use of the Acrobot system in UKR resulted in fewer post-operative ‘outliers’ compared with the control group.

Although there are few reports of the outcome following Acrobot assisted surgery the limited short-term data suggest favourable results. Similar to other robotic technology, long-term studies need to be conducted to determine surgical efficacy.

**Autonomous robotic systems**

These systems offer a theoretical alternative to passive surgery systems which monitor the surgeon throughout the operation, whereas autonomous systems complete the case without surgical assistance. While they are in use, the surgeon is in control of an emergency shut-off switch, while the robot operates independently. Currently, autonomous systems are still under investigation for use in orthopaedic surgery.

A historical example of such a system is the ROBODOC (Curexo Technology Corporation, Fremont, California), which has now fallen out of favour with the arthroplasty community. Developed as a prototype by IBM in the mid-1980s, this system was introduced for use on patients in 1992. The earliest trials conducted with it involved robotic assistance with total hip replacement (THR). Statistically significant improvements in fit, fill and alignment were demonstrated when it was compared with conventional techniques. This system was popular, especially in Germany in the 1990s, but experienced a decline in use amidst safety concerns.

Recently, a hybrid semi-autonomous robotic system has gained popularity as an innovative use of applied technology in orthopaedic surgery. These novel systems consist of small, bone-mounted robots that are hailed as being more efficient and cost-effective than the larger robotic systems currently in use. The mini bone-attached robotic system (MBARS) robot, which was developed at Carnegie Mellon University, Pittsburgh, Pennsylvania, mounts onto the femur and completes the bone resection cuts during TKR.

A similar robotic TKR system (Praxiteles; Praxim Ltd, Grenoble, France), is being developed in France. Similar to many new technologies in the surgical sciences, further development and testing are needed before assessing the efficacy of these small, bone-mounted technologies.

**Passive surgery systems (computer navigation in arthroplasty)**

Computer-assisted or computer navigation surgery systems, also called passive surgery systems, monitor progress and provide surgeons with data during procedures. These systems are used peri-operatively: 1) to assess joint irregularities and joint biomechanics; 2) to make recommendations on how to continue with the procedure, when assessing ligament balancing, for instance; and 3) to monitor the accuracy of the bone cuts. The individual design of
these systems is proprietary but many have several cameras which track surgical instrumentation, boney geometry, and alignment. The cameras are positioned above the patient and often communicate with light-emitting diodes (LEDs) on the boney landmarks and the surgical and navigation instruments.15 Passive surgery systems provide detailed information to the surgeon, who always has the option to over-ride the system’s suggestions. Although the computer in these systems provides data and recommendations, it does not limit the surgeon to pre-determined ‘safe’ cutting zones. This type of system offers greater accuracy over conventional templating in attaining less deviation from the pre-operative plan, especially for lower-volume surgeons or those who are early in the learning curve.15,20,21 Passive systems also provide assistance to surgeons during UKR by facilitating more accurate radiological placement of the components.21-24 Pearle, Kendoff and Musahl22 and Cobb et al6 reported that computer-guided navigation enabled component positioning to within 2° of the pre-operative plan in all cases. In these studies, component positioning was more variable in the cases performed without the aid of computer navigation; 60% of the UKR components were not ideally positioned radiologically.6,22 Other authors have reported that alignment of the femoral and tibial components, tibial slope and the mechanical axis were improved using passive surgery systems.25-31 Finally, computer-aided arthroplasty has improved soft-tissue balance, which is not measured routinely during conventional joint replacement.32,33

However, not all studies have reported improved outcomes with the introduction of computer navigation or passive surgery systems. Lützner et al34 reported no difference in post-operative radiological parameters when using computer navigation in TKR. Yau et al35 also showed no improvement in the radiological outcome measures; in particular, there was no difference in overall limb alignment or alignment of the femoral or tibial component in a retrospective review of 52 computer-navigated versus 52 conventional TKRs.32 Although Kamat et al36 reported better femoral and tibial alignment, these radiological improvements did not result in improved Oxford knee scores37 at a follow-up of one to five years.36 Further, computer-assisted systems have a limited ability to assess rotational alignment, as several studies have concluded that rotational alignment remains inadequately addressed by current passive systems.29,30,38

**Limitations of robot-assisted surgery**

There are financial barriers limiting the widespread use of robotics in orthopaedic surgery. The start-up cost for owning or obtaining a robotic system is often prohibitive for many institutions. Furthermore, these systems require continuous calibration of hardware and software upgrades, resulting in additional costs. Institutions must conduct a complex evaluation of financial feasibility, accounting for operative volume and potential profit, when exploring the use of robotics. Many smaller hospitals or lower volume centres do not have an adequate case load or the specialised surgical expertise necessary to justify the use of these costly systems.15 Passive surgery systems typically have an associated cost of $150 000 to $300 000; although this may be as high as $800 000.39,40 As of August 2010, the popular RIO system manufactured by MAKO costs $793 000 for the robotic platform and $148 000 for the partial knee application software. To date, the financial justification for these systems has not been determined. Although the improved short-term results of lower blood loss and faster rehabilitation supports their use,40,41,42 more studies are needed to determine if robotics truly improve the long-term outcome after surgery.40,43

Proponents of these systems highlight features that might reduce hospital costs, including shorter operative time, fewer complications, and reduced hospital stay.15 As commercially available robotics are more frequently used, the market will determine if the cost and benefit of these systems justify their use.

In addition, concerns other than economics have slowed the integration of robotics into orthopaedic surgery. Questions regarding safety have resulted in hospitals in Germany discontinuing use of ROBODOC.15 Companies have experienced difficulties in engineering a system that is able to work successfully with soft tissues that are mobile and move and change shape during surgery. It has been difficult therefore to develop robotic technology that appreciates the nuances of soft-tissue dissection. In contrast, bones retain their gross anatomical structure, so engineers have focused their efforts on creating systems that perform bone resection.22

The use of the autonomous robotic system was thought to increase the incidence of both nerve damage and infection.15 In addition, the use of ROBODOC has been associated with increased operating times and blood loss.6,16,44 Further, Davies et al15 associated the use of these robots with an increased rate of litigation, which was thought to be a due to a perceived reduction in the involvement of the surgeon in the operation. The many problems encountered with the autonomous robotic systems have led many surgeons to favour of tactile systems. However, most surgical centres in the United States still offer only conventional, non-robot-assisted orthopaedic surgery.

The use of robotic surgery systems has recently increased, with promising short-term improvements in surgical outcomes compared with traditional orthopaedic procedures. The technological innovations in robotic assistance have allowed surgeons to improve pre-operative planning and its execution at operation, resulting in greater accuracy and precision, for example during UKR.21-31 Unfortunately, economic barriers and the lack of prospective, long-term, clinical outcome data have limited the widespread adaptation of robotic technology. Currently, most literature supporting the use of robotic surgery systems comprises studies demonstrating levels of evidence in
categories III, IV and V only. However, as the technology continues to improve and become more accessible, robotic-assisted orthopaedic surgery has the potential to revolutionise how surgery is performed.

The author or one or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article. In addition, benefits have been or will be directed to a research fund, foundation, educational institution, or other non-profit organisation with which one or more of the authors are associated.

References


