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ROBOTICS FOR SURGERY

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■ **Abstract** Robotic technology is enhancing surgery through improved precision, stability, and dexterity. In image-guided procedures, robots use magnetic resonance and computed tomography image data to guide instruments to the treatment site. This requires new algorithms and user interfaces for planning procedures; it also requires sensors for registering the patient's anatomy with the preoperative image data. Minimally invasive procedures use remotely controlled robots that allow the surgeon to work inside the patient's body without making large incisions. Specialized mechanical designs and sensing technologies are needed to maximize dexterity under these access constraints. Robots have applications in many surgical specialties. In neurosurgery, image-guided robots can biopsy brain lesions with minimal damage to adjacent tissue. In orthopedic surgery, robots are routinely used to shape the femur to precisely fit prosthetic hip joint replacements. Robotic systems are also under development for closed-chest heart bypass, for microsurgical procedures in ophthalmology, and for surgical training and simulation. Although results from initial clinical experience is positive, issues of clinician acceptance, high capital costs, performance validation, and safety remain to be addressed.

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INTRODUCTION

Over the past decade, robots have been appearing in the operating room. Robotic technology is now regularly used to aim endoscopes in minimally invasive surgery and to guide instruments to tumors in brain surgery. The use of a robot to shape bones in hip replacement surgery was one of the groundbreaking applications (2, 3, 36). Based on three-dimensional (3-D) computed tomography images, the surgeon plans the location of the prosthetic replacement joint within the femur. In surgery, the robot moves a high-speed cutting tool to form the precise shape specified in the presurgical plan. The result is a far better fit between the bone and replacement joint than has been possible with conventional hand-held cutting instruments.

One reason surgical applications are progressing quickly is the large technology base that has been developed in robotics research in the past three decades (11, 37). Results in mechanical design, kinematics, control algorithms, and programming that were developed for industrial robots are directly applicable to many surgical applications. Robotics researchers have also worked to enhance robotic capabilities through adaptability (the use of sensory information to respond to changing conditions) and autonomy (the ability to carry out tasks without human supervision). The resulting sensing and interpretation techniques that are proving useful in surgery include methods for image processing, spatial reasoning and planning, and real-time sensing and control.

To understand the advantages of using robots in surgery, it is helpful to consider the differences in human and machine characteristics (summarized in Table 1); many promising applications are based on unique robotic capabilities. One key difference is precision and accuracy, or more generally, the ability to use copious, detailed, quantitative information. The combination of 3-D imaging data, computers, and intrasurgical sensors, for example, allows robots to accurately guide instruments to pathological structures deep within the body. Another important difference is that specialized manipulator designs allow robots to work through incisions that are much smaller than would be required for human hands or to work at small scales, where hand tremor poses fundamental limitations.

Humans are superior, however, at integrating diverse sources of information, using qualitative information, and exercising judgment. Humans have unexcelled dexterity and hand-eye coordination, as well as a finely developed sense of touch. Unlike interaction with robots, interaction with human members of a surgical team for instruction and explanation is straightforward. These differences in capabilities mean that current robots are restricted to simple procedures, and humans must provide detailed commands, using preoperative planning systems or by providing explicit move-by-move instructions. Even in the most sophisticated systems, robots are specialized to specific tasks within procedures; humans must prepare the patient, make many of the incisions and sutures, and perform many other functions. Robotic systems are best described as ‘‘extending human capabilities’’ rather than ‘‘replacing human surgeons.’’

Humans	Robots
Strengths	Strengths
Strong hand-eye coordination	Good geometric accuracy
Dexterous (at human scale)	Stable and untiring
Flexible and adaptable	Can be designed for a wide range of scales
Can integrate extensive and diverse information	May be sterilized
Able to use qualitative information	Resistant to radiation and infection
Good judgment	Can use diverse sensors (chemical, force, acoustic, etc.) in control
Easy to instruct and debrief	
Limitations	Limitations
Limited dexterity outside natural scale	Poor judgment
Prone to tremor and fatigue	Limited dexterity and hand-eye coordination
Limited geometric accuracy	Limited to relatively simple procedures
Limited ability to use quantitative information	Expensive
Large operating room space requirement	Technology in flux
Limited sterility	Difficult to construct and debug
Susceptible to radiation and infection	

[a]Adapted from Taylor & Stulberg (75).

In this article, we review enhancements and extensions of surgical practice by robotic technology. The article is divided into two main parts. In the first part, we characterize the main technical approaches under development for robotic surgery. In the second part, we describe specific surgical procedures where robots are used, including orthopedic, general, thoracic, and neurosurgery. We conclude with a discussion of current research issues and promising areas for future research.

ROBOTIC TECHNIQUES FOR SURGERY

Several trends in surgery are contributing to the growing acceptance of robots. Primary factors include the increasing emphasis on minimally invasive surgical techniques and the widespread availability of 3-D image data. Other robotic characteristics, particularly stability and the ability to work at small scales, provide the incentive for additional robotic applications.

Minimally Invasive Procedures

Over the past decade, several surgical specialties have been rapidly transformed by minimally invasive surgery (also called minimal access surgery) (12). A central example is laparoscopic cholecystectomy, or gallbladder excision, a common procedure that is executed almost exclusively using minimally invasive surgery techniques. Surgeons work through a set of three to five incisions approximately 1 cm in size. Long-handled instruments are used to grip and cut tissue within the body, and a video laparoscope provides a view of the internal operating field. Because this procedure avoids the long incision through the abdominal wall used in the conventional open procedure, patients recover more quickly. Benefits include greatly reduced discomfort, improved cosmesis, reduced convalescence and hospitalization costs, and less time away from productive work. Minimally invasive approaches have produced the same benefits in a number of other procedures, such as arthroscopic knee reconstruction and thoracoscopic lung resection.

The necessity of working through a few fixed incisions places severe limitations on dexterity in manipulation, and only a few procedures are possible with the current hand-held instruments. Lateral movement of the instrument shaft is not possible at the incision, which thus acts as a fulcrum, reversing the directions of the surgeon's hand motions at the instrument tip and varying the mechanical advantage as the instruments move in and out. The video monitor is often located on the far side of the patient, and the difference in orientation between the endoscope and the monitor requires the surgeon to perform a difficult mental transformation between visual and motor coordinate frames (76). Contact force perception is impaired by friction and varying mechanical advantage at the incision, and distributed tactile information is absent (34).

Robotic manipulators promise to solve many of these problems. The challenge is to design devices with good dexterity and intuitive control that can be inserted through small incisions. One focus is the development of general purpose systems that can execute a range of procedures in general, thoracic, and gynecological surgery (9, 31, 47). These systems are often configured so that the surgeon sits at a console in the operating room and uses a master control manipulator that sends commands to the robots performing the surgical procedure (Figures 1 and 2). Video images, and sometimes force sensations, are reproduced at the surgeon's console. Other systems under development are aimed at specific access modalities, such as percutaneous needle puncture and transurethral prostate resection. There are also systems that take advantage of robotic ability to perform stable and untiring holding tasks, such as endoscope pointing and organ retraction, and to work at microscopic scales.

Image-Based Procedures

Another catalyst for robotic surgery applications has been the development of noninvasive imaging techniques, including 3-D modalities such as computed tomography (CT) and magnetic resonance imaging, and 2-D techniques such as

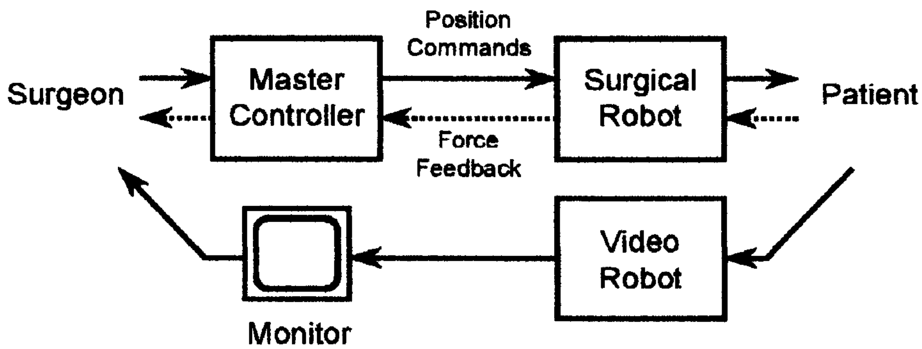

FIGURE 1 Information flow in robotic systems for minimally invasive surgery. The surgeon moves the master manipulators; these motions are sent as position commands to the robotic instruments that manipulate tissues within the patient's body. The surgeon views the internal operative field through video images from an endoscope, which is manipulated by another robotic system. Some systems also furnish audio, force, or tactile information.

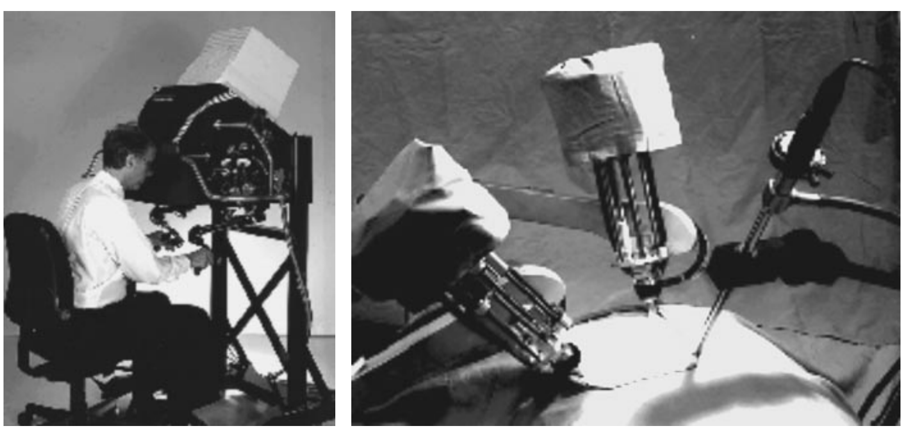

FIGURE 2 Minimally invasive telesurgery robots. Left: surgeon's control console. The surgeon grasps the master manipulator linkages, which also provide force feedback to allow the surgeon to feel the forces that the remote robot is applying at the surgical site. Video monitors (located above the workspace) are viewed in a mirror so that images of the instruments are registered with the master manipulator. Right: minimally invasive surgical robot system. Instruments are shown inserted through small incisions. Left and center modules are manipulators, right module is an endoscope. (From Hill JW, Jensen JF. 1998. Telepresence technology in medicine: principles and applications. *Proc. IEEE* 86(3): 569–580. Reprinted with permission.)

ultrasonography, fluoroscopy, and conventional X-ray radiography. Because these images can reveal the precise location of pathologies, new computational and mechanical tools can guide treatments to the pathology while sparing the surrounding healthy tissue. A typical example is biopsy and resection (removal) of brain tumors (28, 46). Preoperative magnetic resonance imaging can locate the tumor precisely within the skull. After opening the skull, a robot or human surgeon can guide instruments directly to the tumor, based on the image data. Collateral damage to brain tissue is minimized, and because brain structures can be distinguished in preoperative images, the instrument path can be planned to avoid critical regions. Procedures of this type require the solution of three central problems: planning, registration, and navigation, all of which are detailed in the sections that follow.

Planning For planning, the preoperative images must be processed to reveal the essential structures and then presented to the clinician in a suitable form. In some systems, path-planning algorithms operate on the image data, and the results are presented to the surgeon for validation (e.g. 36, 80). The planning process often begins with segmentation of the image data into physiologically meaningful regions. In current procedures, the clinician may perform this operation mentally, but there is considerable interest in automated segmentation. Many approaches are under development, including statistical categorization, matching between anatomical atlas and image data, and physiological approaches such as modeling growth patterns to determine organ shape (5, 49, 81). In the brain tumor example, segmentation requires identification of the location and boundary of the tumor and separation of the various component structures of the brain. Precise segmentation is essential to avoid removing healthy tissue or leaving residual malignancy. Figure 3 (see color figure) shows the output from an image-guided neurosurgery planning and navigation system (28).

The processed image data is then presented to the surgeon for analysis of the patient-specific anatomy and specification of the treatment plan. For brain tumors, this user interface must provide a method for interactively displaying 3-D imaging data on a 2-D computer screen; it must also provide a method to specify the incision point and instrument path. For some procedures, such as hip replacement surgery (see below), computational algorithms automatically calculate an optimal treatment plan, which is presented to the clinician for verification (e.g. 19, 36, 80). Planning methods must take into account the specifics of the organs involved as well as the treatment methodology, so many different approaches to the computational and user interface aspects have been developed. A sampling of these systems is presented below.

Registration To implement this preoperative plan in the operating room requires registration of the image data with the patient's anatomy (44, 69). Registration finds the correspondence between points in the preoperative image data and points on the patient's anatomy on the operating table. Two general approaches have been developed: fiducial-based and shape-based schemes. In the former approach, fiducials, or markers, are attached to the pertinent anatomical structure prior to imaging. From the image data, the robot control computer knows the location of the pathology with respect to the fiducials. During surgery, the markers are exposed and a sensor system conveys their location to the computer. Many sensing systems can be used for determining fiducial location. The most direct is a probe attached to the robot manipulator itself, so that when the robot contacts a fiducial, its location in the robot's coordinate space is immediately determined. From contact with several fiducials, the complete spatial transformation between the preoperative image and the patient can be found.

A number of sensing systems are used in surgery (51, 70). One of the most common is the optical tracker. Light-emitting diodes or reflective targets are attached to a probe, and a set of cameras or optical sensors view the probe from known locations. Triangulation can then determine the location of each target in the robot coordinate frame; submillimeter resolutions are readily achieved. Other sensing techniques include electromagnetic transceivers, articulated probe arms, and ultrasonic and laser range finders. Many of these tracking modalities are available as an integrated part of commercial image-guided treatment systems.

One problem with fiducial-based registration is that the attachment of the markers, which must be carried out prior to imaging, can be a significant surgical procedure in itself. For example, the ROBODOC system for hip replacement surgery uses fiducials that are pins implanted in the femur at both the proximal and the distal ends (see below). This adds time and cost to the robotic procedure and can cause significant discomfort for the patient.

The alternative approach, shape-based registration, avoids these problems by fitting the shape of anatomical structures from intraoperative measurements to the preoperative image data. The patient measurements can be obtained from a variety of sensing techniques, including tracing curves on the pertinent anatomical structure with an optical tracker probe, scanning the surface with a laser range finder, or processing video images of the patient. The result is a description of the shape of the anatomical structure in patient coordinates. A computational algorithm then finds the spatial transformation that minimizes the error between the intraoperatively sensed shape and the shape that has been segmented from the preoperative image data.

There are many other variants on the registration problem. One potentially advantageous approach uses readily obtained 2-D ultrasound or X-ray images as the intraoperative sensing technique. The resulting ''slices'' or projections of the anatomy are then fitted to the 3-D preoperative image data (20, 77). A significant problem in registration is correcting for motion of the patient or deformation of tissue during surgery. This is particularly important in neurosurgery, where swelling of the brain follows a craniotomy. Deformable template matching and biomechanical models that incorporate response to mechanical loading or the edema process have been proposed as a way to deal with this problem (41, 56a). Other tracking approaches use video images to follow patient motion in real time (27). Verification of the accuracy of registration techniques has also become an important research question (17, 25). Because it sets fundamental accuracy limits, registration is important for all areas of image-guided therapy and has attracted a great deal of research interest in recent years.

Navigation Following registration, the preoperative plan and image data can be used for navigation or guidance, by either a robot or a human surgeon. In the case of a robotic manipulator handling an instrument, the sensors in the robot's joints are used with the kinematic model of the manipulator to control the motion of the instrument in a fixed coordinate frame (11). Because the patient and the image data have been registered with this frame, the control computer can relate instrument motion to the patient's anatomy and the presurgical plan. For a human surgeon, guidance is provided for maneuvering hand-held instruments. Sensors track the motion of the instruments, and a computer displays motion instructions to enable the surgeon to navigate to the pathological tissue (28). The choice of robotic versus manual navigation is based on a number of factors, including cost, implementation difficulty, clinical acceptance, and safety concerns. In both approaches, the treatments are enabled by the use of computers and sensors to manipulate quantitative image data in ways that are impossible for humans alone. Further development of robotic technology can be expected to lower development and system costs, and to increase precision so that in the future more of the manual procedures may be executed robotically.

Interaction Modes

Surgeons can interact with robots in many ways. One fundamental categorization is in terms of the level of autonomy exercised by the robot. Currently, a few procedures are executed autonomously, i.e. the robot carries out a preoperative plan without immediate human intervention. Examples are found in hip joint replacement (36) and radiosurgery (66), where the complex or repetitive optimal paths that are calculated would be impossible for a human surgeon to follow with sufficient precision. In this situation, the surgeon plans and sets up the procedure, then monitors its execution to ensure compliance and safety.

Other procedures are performed interactively or assistively, meaning the surgeon and robot share control (79). One example is a robotic system for bone cutting in knee joint–replacement procedures (32). The surgeon grasps the cutting tool at the end of a low-impedance robot manipulator and moves the tool to reshape the bone to fit the prosthetic joint. The robot monitors the surgeon's actions and permits free motion in the appropriate cutting region but applies forces to prevent motion into regions where bone should not be removed. This allows the surgeon to supervise and control the robot, using innate human sensing and judgment, while it also provides ''active constraints'' that increase safety and accuracy of the cutting process. This approach may also improve acceptance of robotic systems by surgeons and patients, as the surgeon remains in control of the procedure. Robots for assistive control applications may require new manipulator designs; most robots are designed for high stiffness to ensure geometric accuracy at the tip in the presence of variable task loads. This makes it difficult to design a sensing and control scheme that allows the robot to follow the surgeon's hand without the application of large forces or significant time delays.

At the other extreme of the autonomy scale, the minimally invasive surgical robot systems described in the previous section are often controlled explicitly by the surgeon. Each motion the surgeon makes with the master manipulator at the control console is transmitted to the robot working inside the patient's body (Figures 1 and 2). The surgeon formulates all motion commands on the basis of sensory information returned from the surgical site, which usually consists of video images. Because the master manipulator is physically separate from the surgical robot, this control mode falls under the category of teleoperation, even though the surgeon is usually located in the operating room with the surgical robot (67a).

Researchers have proposed that this technology will allow surgeons to treat patients from a considerable distance (31, 62). This could reduce the need to transport patients to highly specialized surgeons and avoid exposing surgical personnel to hazardous conditions in wartime or following natural disasters. A central problem is communication delays: Satellite links, for example, often have round-trip delays that last from a fraction of a second to several seconds. This can greatly slow task execution, as the surgeon must pace the procedure to wait to see effects of commanded motions. In the case of force feedback, it has been known for decades that delays of this magnitude can cause instability of the robot control system, although various techniques can help to minimize this problem (67a, 68). A less ambitious application is telementoring, where an experienced surgical specialist can observe and advise surgeons performing a procedure in a distant location. Robotics permits new forms of interaction in telementoring, such as giving the mentor control of the endoscopic camera (65). It remains to be seen whether the benefits of long-distance telerobotic surgical applications will outweigh the technical hurdles, acceptance barriers, and attendant costs (39).

Limitations of Robotic Surgery

There are, of course, many limitations to the application of robotics to surgery. Currently, the mechanical design of manipulators limits dexterity, particularly for minimally invasive procedures with severe size constraints. There is considerable room for improved kinematic configurations, as well as more compact and efficient actuator and transmission technologies. In terms of sensing and control, robots are controlled by computers and thus share many of their all-too-familiar shortcomings, especially for autonomous operation. Robots follow instructions literally, are unable to integrate diverse sources of information, and cannot use qualitative reasoning or exercise meaningful judgment. Although complex 3-D imaging information can be preprocessed to allow execution of very precise tasks, robots have a limited ability to use information from disparate sensors to control behavior during the course of a procedure. Increasing computational power may improve robot control capabilities, but the resulting complexity makes it increasingly difficult to program and debug these systems.

SURGICAL APPLICATIONS

Robotic technology is finding its way into diverse surgical procedures, both revising the way current procedures are executed and enabling new procedures. We review the current state of research for the main surgical specialties that have been the focus of robot applications, emphasizing orthopedics, general and thoracic surgery, and neurosurgery.

Orthopedic Surgery

Orthopedics was one of the first areas of surgery in which robot applications were developed. Compared with soft tissues, bones are relatively easy to manipulate and deform little during cutting, so image-guided techniques are relatively straightforward to implement. The result is that robotic procedures can result in far better agreement with a preoperative plan than with the analogous manual procedure. Orthopedic applications that have received the greatest attention are hip and knee replacement and spinal fusion; additional work is under way in a variety of other areas, including craniofacial reconstruction and fracture treatment.

Total Hip Arthroplasty: Femur Preparation The replacement of hip joints that have failed as a result of disease or trauma has become commonplace. The procedure begins with disarticulation of the joint and removal of the proximal head of the femur. A metal and polymer prosthetic cup is then placed in the acetabulum. The femoral implant consists of a long metal shaft (up to 220 mm) that is inserted into a deep cavity that must be formed along the proximal axis of the femur (52). The prosthetic components are shown in Figure 4.

In the current manual procedure, the surgeon cuts the cavity by forcing handheld broaches and reamers into the femur, which leaves a rough and uneven surface. Until recently, the implant was cemented in place in this pocket, but long-term postoperative data indicated that the cement could crack, loosen, or cause osteolysis, leading to failure of the implant. Newer cementless implants have a porous metal surface and rely on natural bone growth into the metal for fixation. This ingrowth requires close proximity (0.25 mm or less) between the bone surface and the implant, so long-term success is highly dependent on a tight fit between the implant and the femur (52).

The need for improved precision led to the creation of a robotic approach to forming the femoral cavity. Development of the ROBODOC system began in the mid-1980s, and it is now commercially available in Europe and is undergoing FDA approval trials in the United States (36). The system provides two main advantages over the manual procedure. First, clinical trials have confirmed that

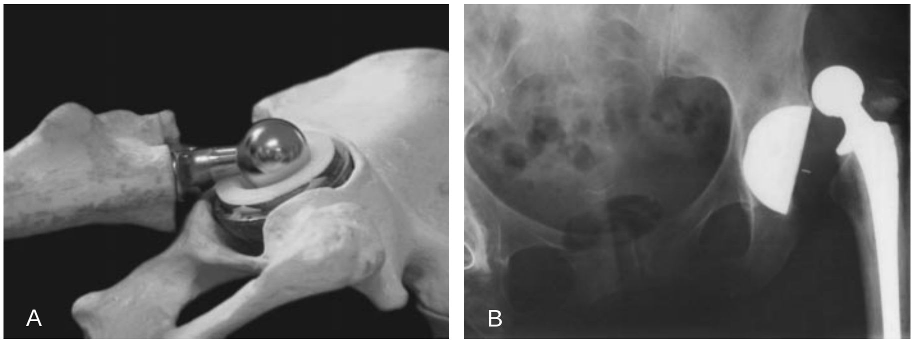

FIGURE 4 *A.* Prosthetic femoral implant (*above*) and acetabular cup (*below*) for total hip replacement surgery. *B.* X-ray showing dislocated prosthetic components in hip. (*A.* from Moody JE, DiGioia AM, Jaramaz B, Blackwell M, Golgan B, et al. 1998. Gauging clinical practice: surgical navigation for total hip replacement. In *Proc. Med. Image Computing and Comp.-Assisted Intervention, Cambridge, Mass,* ed. WM Wells, A Colchester, S Delp. Cambridge, MA, p. 421. Berlin: Springer-Verlag. Reprinted with permission. *B.* from Simon DA, Jaramaz B, Blackwell M, Morgan F, DiGioia AM, et al. 1997. Development and validation of a navigational guidance system for acetabular implant placement. In *Proc. Comp. Vis., Virtual Reality Robotics Med., Med. Robotics Comp.-Assisted Surg., 1st, Grenoble, France,* ed. J Troccaz, E Grimson, R Mosges, p. 583. Berlin: Springer-Verlag. Reprinted with permission.)

the femoral pocket is more accurately formed. Second, because of the need to provide precise numerical instructions to the robot, preoperative CT images are used to plan the bone-milling procedure. This gives the surgeon an opportunity to optimize the implant size and placement for each patient.

The robotic procedure begins with preoperative placement of three titanium pins in the femoral condyles and greater trochanter for registration purposes. Next, the patient undergoes a CT scan, which is loaded into presurgical planning software running on a personal computer. The system interactively displays various views of the image data, and the surgeon selects the appropriate implant from a library and then specifies its placement, considering factors such as leg kinematics and bone density.

In the operating room, the surgical team places the acetabular cup and removes the head of the femur, as in the manual procedure. The femur is rigidly clamped by a ‘‘fixator’’ that is attached to the base of the robot to ensure a fixed, known spatial location. The registration pins are exposed, and a probe on the tip of the robot arm is brought into contact with each pin, which completely specifies the transformation between the preoperative plan and the physical location of the femur. A safety check system confirms that the robot probe locations and the preoperative image show the same spatial relationship among the pins. A high-speed milling device at the end of the robot arm then cuts the femoral cavity. The control of ROBODOC is essentially autonomous: the robot follows the planned cutting paths without the surgeon's guidance. After the pocket is milled, the surgeon continues as in the manual procedure.

The first human trial of the system took place in 1992. Recent reports on approximately 130 hip replacements from an ongoing clinical study in the United States used radiographs to compare ROBODOC-treated patients with a control group (2). The ROBODOC cases showed significantly less space between the prosthetic and the bone. Placement of the implant was also improved. Furthermore, no intraoperative femoral fractures occurred for the ROBODOC group, whereas three were observed in the control group. In Europe, the regulatory environment has permitted wider deployment of the system. Between November 1994 and February 1998, more than 1000 patients were successfully treated at 17 sites in Germany and Austria (3). The results also showed improved prosthetic fit, and the overall complication rate was reduced to 11.6% from the reported manual procedure rates of 16.6% to 33.7%. In addition, the surgical time decreased dramatically as surgeons gained experience with the system and modified the procedure: the first 10 cases averaged 220 min, whereas the current level is 90–100 min (4).

Although results of these studies show that the system successfully achieves the goal of improved fit, there are a number of difficulties that are common to many image-guided surgical procedures. One area for improvement is the traumatic pin placement procedure and slow pin-finding registration process. Work is under way to reduce the number of pins and then to eliminate them altogether, using other registration techniques (71). Another issue is the complex method for fixing the femur to the base of the robot, which is time consuming to set up and can cause postoperative pain in the knee. A related problem is motion of the bone within the fixator during cutting. Currently, a separate sensing system is required to check for motion; if bone shift is detected, cutting is interrupted and the registration process must be repeated. Several incidents of femur motion can push the surgical time over the limit of acceptability. An improved fixation technique or continuous registration method could eliminate these problems. Finally, although prosthetic fit and positioning appear to be improved, it is crucial to address the question of whether this improves treatment in the long term, as the current orthopedic literature does not show a significant correlation between implant fit and long-term outcome (2).

Total Hip Arthroplasty: Acetabular Cup Placement Hip dislocation occurs when the head of the femur disengages from the acetabular cup, as shown in Figure 4. Dislocation is one of the most common postoperative complications following total hip replacement surgery, with a rate of 1%–5% (53). The cause of dislocation is related to a number of factors, particularly malposition of the acetabular implant component. Incorrect positioning can allow the neck of the femoral implant component to impinge on the edge of the cup or a bony prominence on the pelvis, forcing out the femoral head. Unfortunately, current manual alignment devices configure the implant with respect to the gross body axes of

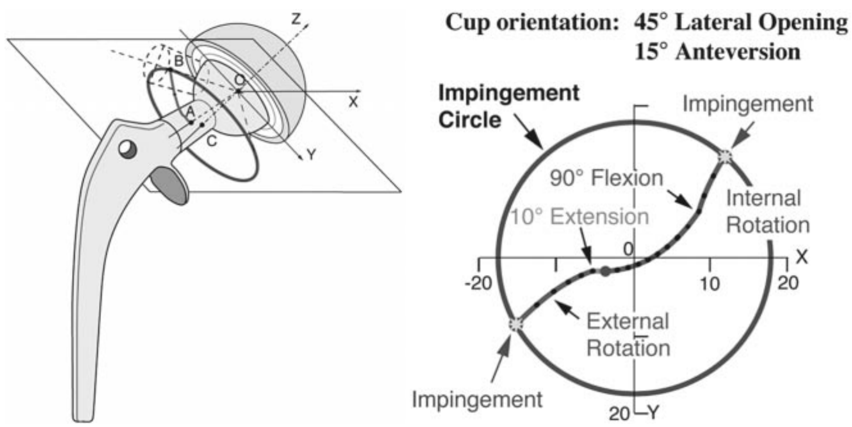

FIGURE 5 Range of motion (ROM) simulator for determining the orientation of the implants at which impingement between femoral neck and acetabular cup would occur. (From Moody JE, DiGioia AM, Jaramaz B, Blackwell M, Golgan B, et al. 1998. Gauging clinical practice: Surgical navigation for total hip replacement. In *Proc. Med. Image Computing and Comp.-Assisted Intervention, Cambridge, Mass,* ed. WM Wells, A Colchester, S Delp. p. 421. Berlin: Springer-Verlag. Reprinted with permission.)

the patient and do not take account of the pelvic orientation on the operating table and individual variations in pelvis geometry.

To reduce this complication, a system for accurate placement of the acetabular cup implant is being developed (53). The HipNav system consists of a preoperative planner, a range of motion simulator, and an intraoperative tracking and guidance system. The range of motion simulator helps surgeons to determine the orientation of the implants at which impingement would occur (Figure 5). Used in conjunction with the planning system and preoperative CT scans, the range of motion simulator permits surgeons to find the patient-specific optimal orientation of the acetabular cup. In surgery, a tracking system must register the location of the pelvis with the preoperative plan and monitor the location of the cup to guide the surgeon to properly place the implant.

Knee Surgery The knee is a complex joint, with large rolling surfaces and an elaborate system of ligaments precisely configured to constrain lateral motion. Navigational systems are under development for various knee-related procedures, such as anterior cruciate ligament replacement (45). Most robotic assistant systems for the knee, however, are aimed at total knee replacement (TKR) surgery. This procedure replaces all of the articulator surfaces by prosthetic components. In TKR, the surgeon uses a jig system to guide bone sawing. Jig placement is based on presurgical X-rays and limited visual information from the exposed bone surface. Because of the lack of intraoperative information, reports suggest that a sizable fraction of current manual procedures result in clinically significant inaccuracies, and up to 40% of the patients are left with patellofemoral pain or limited flexion after conventional TKR surgery (1). The alignment of femur and tibia and the location of ligament attachments are crucial; small displacements (2.5 mm) of the femoral component have been shown to alter the range of motion by as much as 20° (22).

Several robotic TKR assistant systems have been developed to increase the accuracy of the prosthetic alignment. Many of these systems include an image-based preoperative planner and a robot to perform the bone cutting (19). Kienzle et al (38) have developed a system that uses the robot to guide jigs to the correct location, which then allows the surgeon to make accurate bone resections. First, the PUMA 560 robot tracks the motion and locates the center of the femoral head while the surgeon manually flexes and abducts the thigh. The robot uses this landmark as a fiducial in addition to the preoperatively implanted pins to guide the cutting tools to the position where the femur is to be resected. After the surgeon makes the cut for the femur, the robot guides the cutting location for the tibia using the implanted pins. To maintain registration, the pelvis and the ankle are fixed to the surgical table, and the distal femur and proximal tibia are locked with respect to the base of the robot using a six degree-of-freedom arm. This mechanical arm must be attached to the bones without interfering with the activities of the surgeon. Accurate calibration of the robot proved to be one of the largest obstacles for this project. Most industrial robots are built with high repeatability but insufficient positional accuracy. A specialized calibration technique has been implemented, and preliminary results indicate that an accuracy of less than 1 mm and 1° is plausible.

The TKR system developed by Davies and colleagues (16) is similar, but in place of manual sawing, the surgeon guides a cutting tool supported by the robot (Figure 6). The robot can provide a virtual jig by applying resistive force to the surgeon's hand. Areas such as nerves and ligaments are also excluded from the robot workspace. This system is intended to allow the surgeon to stay in control while minimizing human errors. Animal studies have shown that the overall accuracy is approximately 1.3 mm.

Spine Surgery Spinal fusion procedures attach mechanical support elements to the spine to prevent relative motion of adjacent vertebrae. Traditionally, the posterior spine is exposed, then pilot holes are prepared and screws are inserted into the vertebrae using the surgeon's anatomical knowledge and CT films. The screws must accurately reach a deep target without direct visual information. Small lateral and angular errors at the surface can lead to large errors at the screw tip, and the error cannot be monitored continuously during the procedure to avoid radiation overexposure. Compared with hip and knee surgery, these procedures present additional difficulties with registration, including movement of the vertebrae due to respiration and drilling.

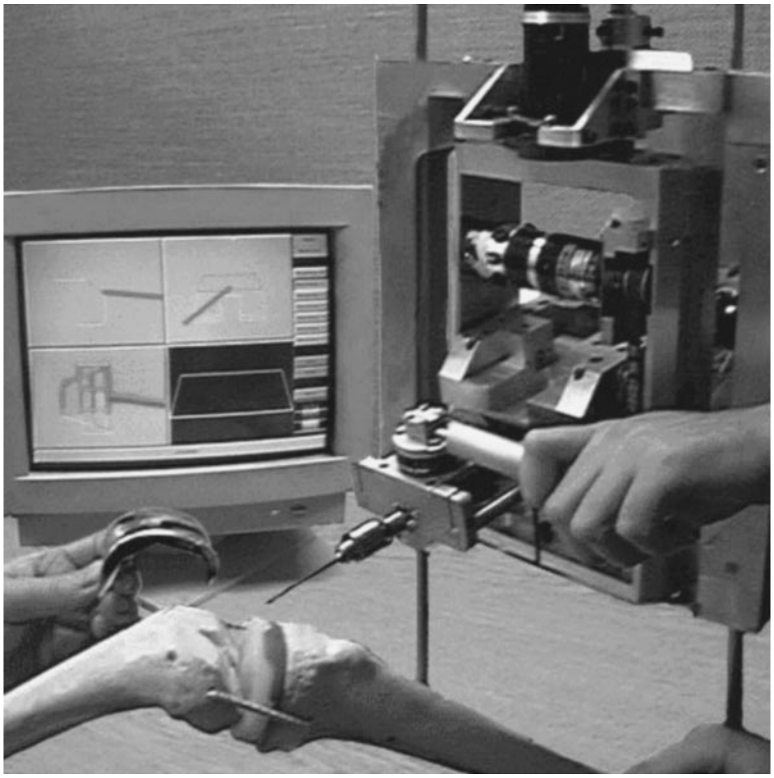

FIGURE 6 Total knee replacement robot. The surgeon guides the cutting tool while the robot generates constraint forces to ensure accuracy and protect key structures. (From Harris SJ, Jakopec M, Hibberd RD, Cobb J, Davies BL, 1998. Interactive pre-operative selection of cutting constraints, and interactive force controlled knee surgery by a surgical robot. In *Proc. Med. Image Computing and Comp.-Assisted Intervention, Cambridge, Mass,* ed. WM Wells, A Colchester, S Delp. pp. 996–1006. Berlin: Springer-Verlag. Reprinted with permission.)

Current research in spinal surgery focuses on image-guided passive assistance in aligning the hand-held surgical drill. Preoperative CT images are integrated with tracking devices during the procedure. Targets may be attached to each vertebra to permit constant optical motion tracking during the procedure. Using these techniques, Merloz et al (50) report a far lower rate of cortical penetration for computer-assisted techniques compared with the manual procedure. Work is under way on the use of intraoperative ultrasound or radiograph images to register the CT data with the patient (43). The screws may then be inserted percutaneously, eliminating the need for exposing the spine.

Neurosurgery

Neurosurgery was the first surgical specialty to use image-guided techniques, beginning with stereotactic frames that were attached to the patient's cranium before the imaging process and remained in place during surgery. The relationship between the frame and lesion observed in the image was used to guide the instruments within the brain. Newer image-guided techniques, sometimes called frameless stereotaxy, use less invasive fiducial markers or video images for registration and optical trackers for navigation of hand-held instruments (27, 28, 44). To enhance stability, accuracy, and ease of use, a number of robotic systems have been developed for these procedures over the past 15 years (e.g. 24a, 26, 40, 46, 48).

One issue in image-guided neurosurgery is shifting of the brain during the procedure, which alters the spatial relationship between the preoperative image data and the anatomy of the patient. Various solutions have been proposed to deal with this problem, including deformable templates for nonrigid registration, sometimes based on biomechanical models of soft tissue (41, 56a). Another solution is to perform the procedure inside an imaging system, which permits continuous monitoring of the anatomy and instrumentation. This requires robotic manipulators that are compatible with the imaging modality and space constraints (48).

Radiosurgery uses a beam of radiation as a surgical instrument to destroy brain tumors. If the angle of incidence of the beam is pivoted through a large range, the beam passes through the tumor at all times but intersects each point of adjacent tissues only briefly (Figure 7). Planning algorithms can optimize the path to gen-

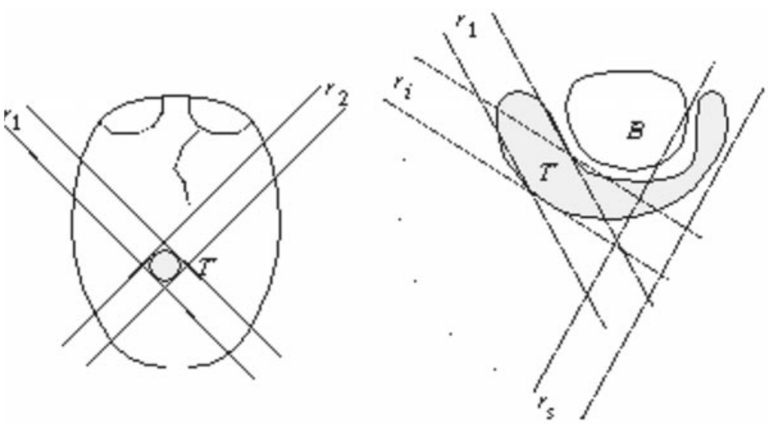

FIGURE 7 Radiation beam for radiosurgery passes through the tumor at all times but intersects each point of adjacent tissue only briefly. (From Schweikard A, Adler JR, Latombe J-C. 1993. Motion planning in stereotaxic radiosurgery. *Proc. IEEE Intl. Conf. on Robotics and Automation, Atlanta,* 1:909–16. Reprinted with permission.)

erate a near-uniform dose throughout the tumor volume and avoid irradiating nearby critical regions (66). Because the radiation sources are large and must follow precise trajectories, robots can be used as motion platforms for this application (Figure 8).

General and Thoracic Surgery

Many minimally invasive procedures in general and thoracic surgery share essential traits. The pertinent anatomy is approached via small incisions through the relatively thin (1–2 cm) abdominal or thoracic wall, accessing an open working volume. The incision acts as a pivot for tools that are relatively free to move inside the body; this pivot constraint poses many challenges in sensing and manipulation for the surgeon. Autonomous robots that use imaging data for guidance are not suitable for these applications because of the dexterity and variety of skills required for manipulating highly deformable soft tissue.

Because video endoscopes can provide direct visual access to the surgical site, surgeon-controlled teleoperated robots promise to help in a number of ways. Specialized mechanical designs add a ‘‘wrist’’ with additional joints near the instrument tip, which can rectify the motion constraint imposed by the incision

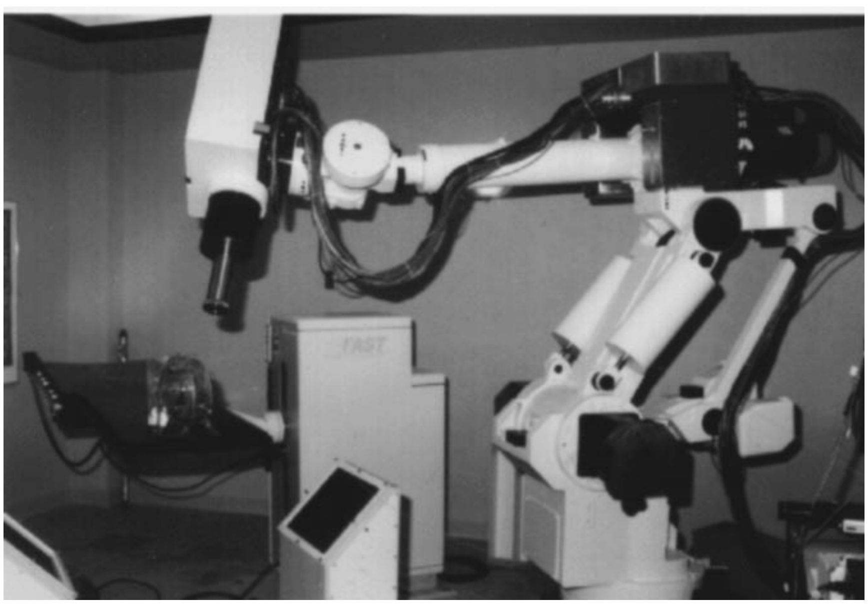

FIGURE 8 Radio surgery robot that uses a modified industrial robot as a motion platform for the large radiation source mounted at the end of the arm. (From Schweikard A, Adler JR, Latombe J-C. 1993. Motion planning in stereotaxic radiosurgery. *Proc. IEEE Intl. Conf. on Robotics and Automation, Atlanta,* 1:909–16. Reprinted with permission.)

(9, 31, 47). With these manipulators, surgeons can orient the instrument to arbitrary angles and reach around anatomical structures. Second, the controller can scale the surgeon's motions so that the robot works at smaller scale than is possible with hand-held instruments. This enables microsurgical procedures using minimally invasive techniques, as has been demonstrated for tubal anastomosis in heart bypass procedures (67, 73). A third advantage is that the control computer can interpose rotational transformations between the surgeon's master control interface and the surgical robot, so that, for example, orientations in the video image match motion direction at the surgeon's hands. Studies indicate that appropriate mappings can improve manipulation performance (42).

Teleoperation is also a promising approach for microsurgery in a number of specialties, including vascular, gynecological, neuro-, and ophthalmological surgery. A number of specialized systems have been developed (31, 64), in addition to the general-purpose telesurgical systems described above with motion scaling capabilities. These systems pose unique research problems, including development of specialized manipulators and grippers, control methods for optimal mapping between the human scale and microscales, and elimination of hand tremor (61, 63).

Minimally Invasive Surgery—Specialized Designs Specialized robotic systems can enable new procedures where access is limited to long lumens, as in gastrointestinal or urinary surgery. One example is transurethral resection of the prostate (30, 54). This procedure, to ameliorate benign enlargement of the prostate, is now a skilled manual process of inserting instruments through the urethra and removing tissue with repetitive cutting motions. In the system developed by Harris et al (30), the robotic system incorporates real-time ultrasonic imaging as well as cutting instruments. The surgeon uses the images to select the volume of the prostate to be excised. As with the ROBODOC system for hip surgery, the robot executes the planned resection autonomously, and the user interface provides the surgeon with continuous information about the progress of the procedure; the surgeon may halt or modify the procedure at any time. By developing a special-purpose mechanism, a number of safety features may be incorporated, including limiting the workspace accessible to the robot to the volume of the prostate, thus eliminating the possibility of more extensive tissue injury in the event of malfunction.

Another example of procedure-specialized mechanism design is robotic endoscopy. The most common application is colonoscopy, where the goal is inspection, biopsy, or treatment of the colon. Conventional endoscopes are rigid tubes, sometimes with a few manually operated joints. The limited articulation capabilities permit access only to the lower portion of the intestinal tract, and the limited conformation may produce large forces that cause considerable discomfort to the patient. There are two robotic approaches to endoscopes for these applications (58). One is a highly articulated mechanism with many joints that can conform to the sinuous passages of the bowel (35, 57). This approach requires incorporating a large number of actuators and sensors into the endoscope structure; size constraints suggest that novel technologies such as shape-memory alloy actuators may be useful here. Robotics research has only partially solved the problem of path planning and control algorithms for mechanisms with many redundant degrees of freedom.

The other approach is a miniature self-propelled robotic ‘‘vehicle,’’ which has the potential to reach the entire gastrointestinal tract. The systems developed by Slatkin et al (71a, 72) and Carrozza et al (7) use an inchworm propulsion mechanism. Collars at the ends of each segment inflate to grip the colon wall, and extensors vary the distance between the collars (Figure 9). Activating these actuators in the correct sequence moves the robot forward or backward within the intestine. The robot trails an umbilical cable that provides power and control signals and returns video and other sensor information. The actuators use low-pressure pneumatic power to conform to the large variation in intestinal diameter

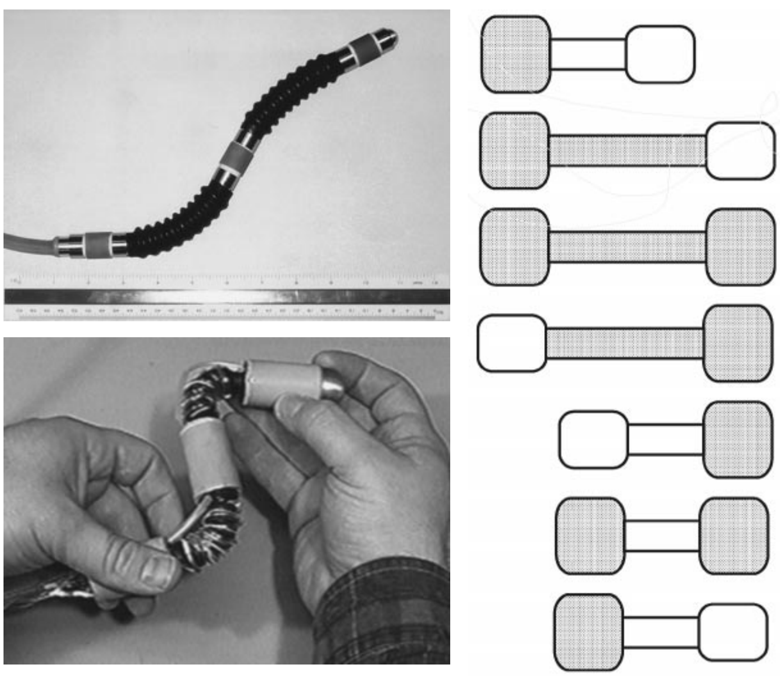

FIGURE 9 Self-propelled robot endoscope. (*Left*) Structure consists of flexible extensors joining inflatable collars, with a trailing umbilical for power and signal transmission. (*Right*) Once cycle of the inflation sequence for these actuators that moves the robot forward within the intestine. Inflated elements are shaded in each step. (Adapted from Slatkin AB, Burdick J, Grundfest W. 1995. The development of a robotic endoscope. In *Exp. Robotics IV. 4th Intl. Symp.*, ed. O Khatib, JK Salisbury, pp. 161–9. Berlin: Springer-Verlag. Reprinted with permission.)

and avoid concentrated local pressure on the intestinal wall. This also minimizes safety concerns associated with electrical actuation.

Another class of robotic system is designed for percutaneous needle puncture. Examples of procedures that are under development for robotics include draining fluid from the pericardial cavity (8) and the renal collecting system (74), and placing a pattern of radiation ''seeds'' for cancer treatment (6, 54). Some of these procedures are possible now with a manually inserted needle, but execution is difficult: Guidance is usually by 2-D images (ultrasound, X-ray, or fluoroscopy), and the surgeon must hit the small, deformable soft-tissue target and miss adjacent critical structures. New image-guided approaches use mechanical arms and multiple fluoroscopic views to aim the needle in three dimensions (59, 74) (Figure

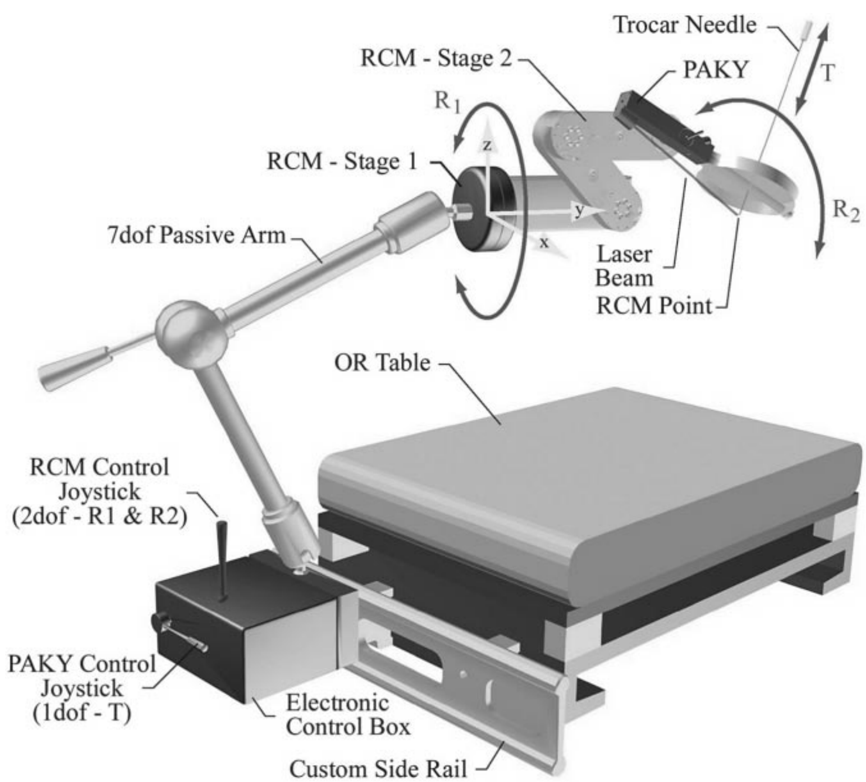

FIGURE 10 Robot for percutaneous needle puncture procedures. The lower joints are positioned and locked manually, while the upper stages are motorized. The needle positioner at the tip is transparent to X-rays to enable radiographic guidance. (From Stoianovici D, Whitcomb LL, Anderson JH, Russell RH, Kavoussi LR. 1998. A modular surgical robotic system for image guided percutaneous procedures. In *Proc. Med. Image Computing and Comp.-Assisted Intervention, Cambridge, Mass,* ed. WM Wells, A Colchester, S Delp, p. 404. Berlin: Springer-Verlag. Reprinted with permission.)

10). Another approach uses optical trackers on an ultrasound head, so a computer can reconstruct the 3-D anatomical structure (8). An optical tracker on the needle holder guides the surgeon to insert the needle into the target. Challenges in these procedures include the 2-D to 3-D registration problem, misregistration from motion of the patient as a result of respiration, heartbeat, or discomfort, deflection of the needle, and the development of intuitive computer interfaces for 3-D guidance.

Stability Enhancement Because robots are stable and untiring, they are effective assistants for a number of surgical procedures. One task that has received much attention is holding endoscopes for minimally invasive surgery. Several robotic systems for laparoscopic general surgery are now commercial products (1a, 21, 23). This function is particularly appealing for robotic implementation because contact with tissue is limited to the sides of the incision, so safety concerns and control complexity are minimized. Various methods for controlling scope pointing have been implemented, from simple instrument-mounted joysticks and foot pedals to voice commands (1a, 23) and head tracking (21). For neurosurgery, Gorodia et al (26) have demonstrated an assistive control system where the surgeon manually guides a robot-mounted endoscope. For procedures such as evacuation of hematomas, this approach may overcome problems with steadiness and precision when the endoscope is supported only by hand. Other applications where stability and lack of fatigue are important include limb holding (18) and organ retraction (60).

TRAINING AND SIMULATION

Robots are also finding applications in surgical training and simulation, where they provide force feedback from computer models of instrument–tissue interaction. In these systems, users manipulate surgical instrument handles that are attached to specialized robot manipulators (Figure 11; see color figure). A computer senses the user-generated motions and commands the robot to apply the forces that would have resulted from the instruments' interaction with real tissue. The computer also generates images of the simulated surgical site. These systems are similar to telesurgical systems where the user interacts with the master manipulator, but here a computer model replaces the actual surgical robot and patient. Systems have been developed for many procedures, including arthroscopic knee surgery (24), tubal anastomosis (56), and laparoscopic surgery (10).

These virtual environment systems offer a number of potential advantages. Compared with cadaver and animal training, costs may be reduced, and compared with conventional patient-based surgical training, there are fewer time and performance constraints. Because these systems measure all of the actions during each procedure, trainees can review their data to analyze technique, and trainers can evaluate progress and skill level. Finally, surgeons can explore new and enhanced surgical techniques, and by incorporating preoperative image data, patient-specific procedures may be rehearsed.

The field of surgical simulation is still in an early state of development. Specialized ''haptic interface'' robots with sufficient fidelity to produce realistic sensations have been available for fewer than 10 years (13, 30a). One unsolved problem is tissue modeling. To determine the correct force to feed back in response to user motions, the system must calculate the deformation of model tissues in real time. Current mechanical modeling techniques, based on the finite-element method, are too slow for real-time use (1b, 10, 15a). In addition, the mechanical properties of many of the tissues of interest have not been measured. Another problem is generation of patient-specific models from 3-D image data. Gibson et al (24) have developed a voxel-based object representation scheme that operates directly on the medical image data structure. This approach can represent volumetric information that is hidden from the surface to allow realistic modeling of deformation, cutting, and tearing of tissues. Limitations of this approach include slow visual rendering and the need for more resolution for haptic feedback.

A central question for these systems is the relevance to actual surgery: Can a simulator effectively train medical students in good surgical skills? A report by O'Toole et al (56) suggests that the answer is yes. This study used a simulator to assess suturing technique. The user interface was a needle holder and forceps attached to force feedback devices (Figure 11). The user could see and feel simulated organs and interact with them in various ways (grasp, poke, pluck, and suture). Physics-based models made the vessels statically and dynamically realistic. Twelve medical students and eight practicing vascular surgeons performed large flexible-vessel anastomosis with the simulator. Their performance was evaluated in terms of errors, accuracy, and tissue damage. The average medical student's score was significantly worse than the average of practicing surgeons for most measures. In addition, performance improved more for the students during the study. Although these results demonstrate that untrained subjects learned the simulated surgical technique, the transference of skills to real surgery was not evaluated.

TECHNICAL AND IMPLEMENTATION CHALLENGES

The results reviewed above demonstrate that robotic technology can enhance surgery in many ways. Surgical robotics has been an active area of research for only a decade, and innovation continues at a rapid pace. In this concluding section, we review some of the leading research problems and consider issues that may constrain widespread clinical acceptance of robotic surgery.

Technical Issues

As discussed above, the great majority of surgical applications take advantage of the unique characteristics of robots. The main benefits may be summarized as improved precision, stability, and dexterity. To extend these benefits to additional procedures will require advances in mechanical design, sensing, and control.

Mechanical Design Currently, many image-guided surgical applications use off-the-shelf industrial robot manipulators. This speeds development and reduces costs, but these devices have not been optimized for the characteristics of specific surgical tasks. For example, most industrial robots are designed for good repeatability but may lack sufficient positional accuracy (38, 40). Similarly, assistive systems that share control between the robot and human surgeon would benefit from the development of low impedance manipulators in place of highly geared, stiff industrial arms (32, 79). Other advantages that can accrue to specialized designs include improved sterility and compatibility with imaging systems (e.g. transparency to X-rays). In teleoperated systems, access constraints have always necessitated the development of new manipulator configurations, but kinematic structures and actuator technologies are far from perfected. These technologies also limit the development of microrobots for medical applications (14).

Sensing and Control In teleoperated systems for minimally invasive or microsurgical procedures, there is substantial room for improvement of control and sensory feedback interfaces. In general, the human factors aspects of these systems have been little studied. Research questions include master manipulator configuration, mapping between master and remote robot coordinate systems, scaling laws for micromanipulation systems, and video, force, and tactile feedback fidelity and bandwidth requirements (31, 34, 42, 63, 67a, 68).

Image-guided procedures have been an area of great success for robotic surgery, but there are many unresolved issues. Improved automatic segmentation and planning systems promise to improve efficiency and accuracy. Areas for improvement in registration include elimination of invasively placed fiducials and methods for nonrigid registration and tracking of tissue deformation in real time. The use of 2-D imaging modalities such as ultrasound in combination with 3-D tracking may lower costs and enable wider application of image-guided techniques (8, 77).

For autonomous robotics in general, almost all successful applications over the past three decades have come in areas where tasks are narrowly specified and the environment is predictable, as in manufacturing. The early success of robotics in orthopedic surgery is due at least in part to the fact that bones are essentially rigid and relatively straightforward to manipulate, immobilize, and cut. The use of robots for autonomously manipulating soft tissue raises a host of new challenges, many without precedent in robotics research.

Currently, large deformation manipulation of soft tissue requires teleoperation, where the surgeon provides the required sensory integration and dexterous control. For autonomous robots to undertake these tasks will require good hand-eye coordination, tactile sensing of the instrument–tissue contact state, and an ability to predict the outcome of manipulative actions. Increased computational power has enabled new capabilities in ‘‘visual servoing’’ of manipulator motion, which begins to address the visual coordination problem (29, 34a). In contrast, integrating tactile information into control is still a largely unsolved problem in robotics, even for rigid objects (33). Alternative sensing schemes, such as real-time continuous magnetic resonance imaging, may prove superior to visual and tactile approaches, but cost and manipulator compatibility issues are severe obstacles. Predicting the results of manipulative actions may require mechanical modeling of the tissue–instrument interaction. Initial research in this area for surgical simulation has showed that conventional techniques are far too slow for use in real-time control (10, 15a, 24).

In addition to these quantitative abilities, the actions of a skilled surgeon are based on broad and deep knowledge of anatomy and surgical technique. For complete autonomy, robots must be able to use such qualitative reasoning and broad sensory integration in control. This will require fundamental advances in several areas of computer science as well as robotics. As a more immediate goal, it may be possible to add semiautonomous capabilities that exploit the quantitative advantages of robots to decrease the demands on the surgeon, enable new procedures, and improve safety.

Clinical Implementation and Acceptance Issues

Safety Safety is an obvious concern for robotic surgery, and regulatory agencies require that it be addressed for every clinical implementation. As with most complex computer-controlled systems, there is no accepted technique that can guarantee safety for all systems in every circumstance (15, 55, 78). Various robotic systems approach the problem in different ways. One common technique is to include passive and active safety mechanisms in the mechanical design of the manipulator. A good example is the AESOP endoscopic pointing robot, used for minimally invasive general surgery (23). The end of the robot arm is attached to the endoscope through a gimbal and a magnetic coupling. Because the incision prevents lateral motion of the endoscope tube, as the robot moves the endoscope in space above the patient, the gimbal allows the endoscope tube to pivot about the incision. This makes it impossible for the robot to apply lateral forces on the incision. The magnetic coupling acts as an emergency release: If forces on the endoscope exceed the magnetic holding force, the endoscope disconnects and falls onto the patient's abdomen, which is unlikely to cause injury.

Examples of designed-in hardware safety features in other robot systems include the use of low-pressure pneumatic power to minimize dangers from electrical actuation (71a, 72), and limiting the size of the robot workspace to eliminate the possibility of damage to tissue away from the intended surgical site (30).

Safety features of the software portion of the system are also essential. In the context of a urology robot, Ng & Tan (55) used mathematical logic to analyze program flow and determine if it is possible for control to evade the safety features incorporated into the code. In addition, they implemented a completely independent safety monitor that can arrest a servo runaway and detect out-of-safe-boundary conditions, using joint encoder signals as input.

Some robotics developers have asserted that it is important to keep control of the procedure in the hands of the surgeon, even in image-guided surgery (32, 78).

For example, the knee surgery system developed by Ho et al (32) (see above) has the surgeon moving the cutting tool while the robot prevents motion outside of the planned workspace. In contrast, the ROBODOC hip replacement system has the robot moving the cutting tool under autonomous control while the surgeon monitors progress (36). Early results with ROBODOC from Europe suggest few problems with clinician acceptance of the autonomous control mode (2–4). As experience with robotic systems increases, the level of comfort with autonomous control may rise. It is, however, undeniably important to design user interfaces so that the surgeon is fully informed of the system's plans and status.

Other Acceptance Issues Robots will be successful in surgery only if they improve patient outcome, lower cost, or both. Unfortunately, in many cases outcome cannot be assessed until many years after the procedure. For example, it may take 15 years to accurately measure the difference in durability of robotic versus manual hip replacements. This is a prohibitive delay, both for the developers of the systems and for the patients who are denied this potentially improved care in the intervening years. As a result, an alternative measure of outcome may be necessary. In the hip replacement case, one measure is comparison of the closeness of the fit between the femur and the implant. As previous bone growth studies have shown that close fit is essential for good fixation, this is a plausible correlate with long-term success of the procedure. The space between the implant shaft and the bone can be measured radiographically soon after surgery, so this provides a means to measure outcome promptly, if indirectly, and facilitate more rapid acceptance. One benefit from early acceptance of robotic technology is that as the number of cases increases, clinicians often improve the procedure, which may result in better outcomes and lower costs (4).

Expense is also an issue with some robots. Although there is a large range in cost, some systems exceed one million dollars. This may reduce the rate of implementation, especially in the early years, when benefits have not been fully realized or documented. As the field matures and engineering expertise with these systems increases, costs will likely decrease. In addition, many robotic systems are now dedicated to specific procedures, so that systems for knee replacement are unable to perform hip replacements, even though the procedures are similar in many respects. With growing maturity of the field, systems may gain flexibility, so that the same robot can be used for a variety of procedures in a surgical specialty, serving to reduce costs.

Finally, we note that the progress reviewed here demonstrates that robotic technology will transform surgery in the coming years. Robots promise to become the standard modality for many common procedures, including hip replacement, heart bypass, and abdominal surgery. This suggests that surgeons, particularly researchers working to enhance and extend the field, will need to become familiar with robotic technology. The same is true for robotics researchers: Creating effective systems requires understanding the demands of surgical procedures and the culture of surgical practice. The research teams that have created groundbreaking systems demanded close collaborations among robotics researchers, computer scientists, and surgeons. Future progress will require similar interdisciplinary teamwork.

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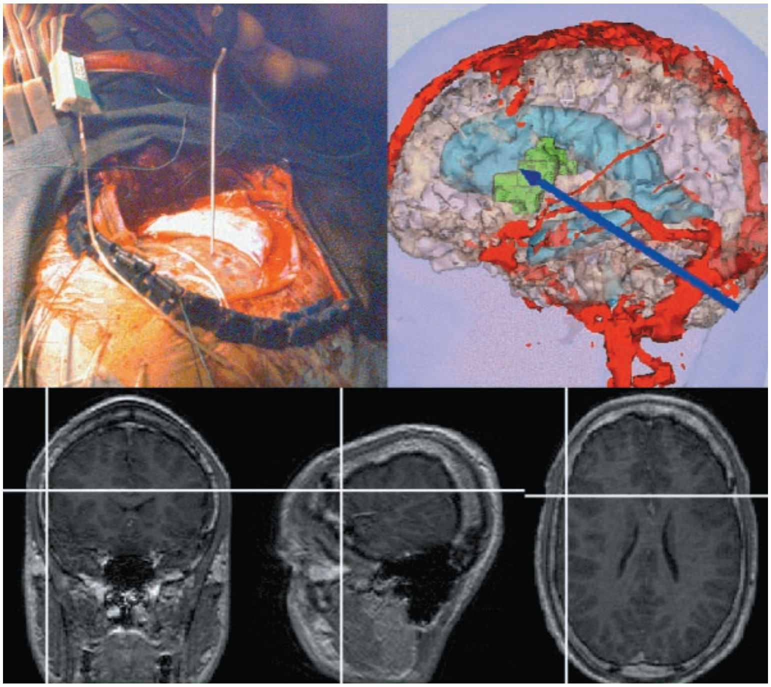

Figure 3 Image-guided neurosurgery planning and navigation system developed by MIT and Brigham and Women's Hospital. (*Upper left)* Photograph of operative field after craniotomy; optical markers on the hand-held probe at the center enable tracking and registration. (*Upper right)* Perspective view of segmented MR image data. Colors indicate normal (*gray, red, blue*) and pathological (*green*) brain structures. *Blue arrow* indicates probe location determined from real-time tracking data. (*Lower images)* Orthogonal views through MR data. Crosshairs show current probe tip location to assist in navigation. (Reprinted with permission from WEL Grimson, MIT.)

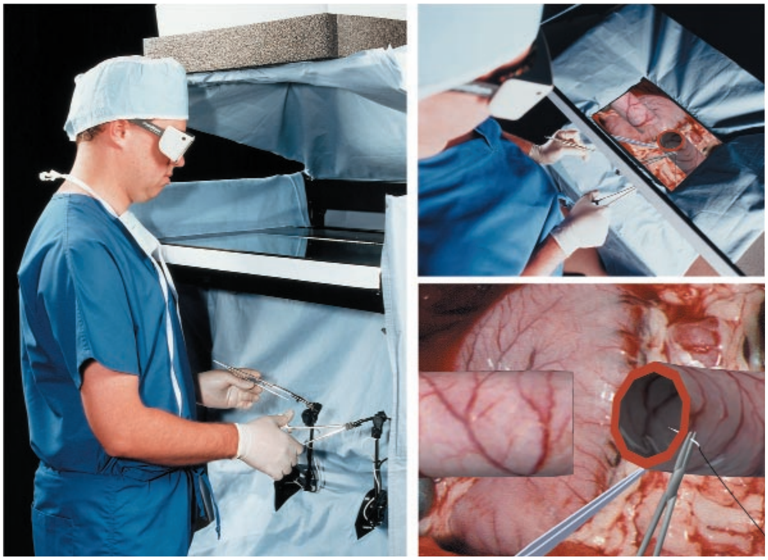

Figure 11 Surgical simulation training system for end-to-end anastomosis procedures. (*Left image*) Using a needle holder and forceps attached to force-feedback devices, the user can grasp, poke, pluck, and suture flexible vessels. (*Upper right*) A mirror arrangement superimposes the 3-D image of the operative field in the correct position relative to the surgeon's hands. (*Lower right*) Mechanics-based models generate forces and images that change realistically in response to contact. (From R O'Toole, R Playter, T Krummel, W Blank, N Cornelius, et al. Assessing Skill and Learning in Surgeons and Medical Students Using a Force Feedback Surgical Simulator. In *Proc. Med. Image Computing and Comp.-Assisted Intervention*, Cambridge, MA, 1998, p. 404. Ed. WM Wells, A Colchester, S Delp. Berlin: Springer-Verlag. Reprinted with permission.)