# Robotic Surgery

## *A Current Perspective*

*Anthony R. Lanfranco, BAS, Andres E. Castellanos, MD, Jaydev P. Desai, PhD,*† and William C. Meyers, MD*

**Objective:** To review the history, development, and current applications of robotics in surgery.
**Background:** Surgical robotics is a new technology that holds significant promise. Robotic surgery is often heralded as the new revolution, and it is one of the most talked about subjects in surgery today. Up to this point in time, however, the drive to develop and obtain robotic devices has been largely driven by the market. There is no doubt that they will become an important tool in the surgical armamentarium, but the extent of their use is still evolving.
**Methods:** A review of the literature was undertaken using Medline. Articles describing the history and development of surgical robots were identified as were articles reporting data on applications.
**Results:** Several centers are currently using surgical robots and publishing data. Most of these early studies report that robotic surgery is feasible. There is, however, a paucity of data regarding costs and benefits of robotics versus conventional techniques.
**Conclusions:** Robotic surgery is still in its infancy and its niche has not yet been well defined. Its current practical uses are mostly confined to smaller surgical procedures.

(*Ann Surg* 2004;239: 14–21)

Robotic surgery is a new and exciting emerging technology that is taking the surgical profession by storm. Up to this point, however, the race to acquire and incorporate this emerging technology has primarily been driven by the market. In addition, surgical robots have become the entry fee for centers wanting to be known for excellence in minimally invasive surgery despite the current lack of practical applications. Therefore, robotic devices seem to have more of a marketing role than a practical role. Whether or not robotic devices will grow into a more practical role remains to be seen.

Our goal in writing this review is to provide an objective evaluation of this technology and to touch on some of the subjects that manufacturers of robots do not readily disclose. In this article we discuss the development and evolution of robotic surgery, review current robotic systems, review the current data, discuss the current role of robotics in surgery, and finally we discuss the possible roles of robotic surgery in the future. It is our hope that by the end of this article the reader will be able to make a more informed decision about robotic surgery before "chasing the market."

## BACKGROUND AND HISTORY OF SURGICAL ROBOTS

Since 1921 when Czech playwright Karel Capek introduced the notion and coined the term robot in his play *Rossom's Universal Robots*, robots have taken on increasingly more importance both in imagination and reality.[1,2] Robot, taken from the Czech *robota*, meaning forced labor, has evolved in meaning from dumb machines that perform menial, repetitive tasks to the highly intelligent anthropomorphic robots of popular culture. Although today's robots are still unintelligent machines, great strides have been made in expanding their utility. Today robots are used to perform highly specific, highly precise, and dangerous tasks in industry and research previously not possible with a human work force. Robots are routinely used to manufacture microprocessors used in computers, explore the deep sea, and work in hazardous environment to name a few. Robotics, however, has been slow to enter the field of medicine.

The lack of crossover between industrial robotics and medicine, particularly surgery, is at an end. Surgical robots have entered the field in force. Robotic telesurgical machines have already been used to perform transcontinental cholecystectomy.[3,4] Voice-activated robotic arms routinely maneuver endoscopic cameras, and complex master slave robotic systems are currently FDA approved, marketed, and used for a

From the *Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia and Drexel University College of Medicine, Philadelphia, Pennsylvania.
This material is based upon work supported by the National Science †Foundation under Grant No. 0079830 and Grant No. 0133471.
Reprints: Andres E Castellanos, MD, Assistant Professor, Department of Surgery, Drexel University College of Medicine. Mail Stop 413, 245 N. 15th Street, Philadelphia PA 19102. E-mail: Andres.E.Castellanos@Drexel.edu.

ISSN: 0003-4932/04/23901-0014
DOI: 10.1097/01.sla.0000103020.19595.7d

variety of procedures. It remains to be seen, however, if history will look on the development of robotic surgery as a profound paradigm shift or as a bump in the road on the way to something even more important.

Paradigm shift or not, the origin of surgical robotics is rooted in the strengths and weaknesses of its predecessors. Minimally invasive surgery began in 1987 with the first laparoscopic cholecystectomy. Since then, the list of procedures performed laparoscopically has grown at a pace consistent with improvements in technology and the technical skill of surgeons.[5] The advantages of minimally invasive surgery are very popular among surgeons, patients, and insurance companies. Incisions are smaller, the risk of infection is less, hospital stays are shorter, if necessary at all, and convalescence is significantly reduced. Many studies have shown that laparoscopic procedures result in decreased hospital stays, a quicker return to the workforce, decreased pain, better cosmesis, and better postoperative immune function.[6–8] As attractive as minimally invasive surgery is, there are several limitations. Some of the more prominent limitations involve the technical and mechanical nature of the equipment. Inherent in current laparoscopic equipment is a loss of haptic feedback (force and tactile), natural hand-eye coordination, and dexterity. Moving the laparoscopic instruments while watching a 2-dimensional video monitor is somewhat counterintuitive. One must move the instrument in the opposite direction from the desired target on the monitor to interact with the site of interest. Hand-eye coordination is therefore compromised. Some refer to this as the fulcrum effect.[9] Current instruments have restricted degrees of motion; most have 4 degrees of motion, whereas the human wrist and hand have 7 degrees of motion. There is also a decreased sense of touch that makes tissue manipulation more heavily dependent on visualization. Finally, physiologic tremors in the surgeon are readily transmitted through the length of rigid instruments. These limitations make more delicate dissections and anastomoses difficult if not impossible.[10] The motivation to develop surgical robots is rooted in the desire to overcome the limitations of current laparoscopic technologies and to expand the benefits of minimally invasive surgery.

From their inception, surgical robots have been envisioned to extend the capabilities of human surgeons beyond the limits of conventional laparoscopy. The history of robotics in surgery begins with the Puma 560, a robot used in 1985 by Kwoh et al to perform neurosurgical biopsies with greater precision.[6,11] Three years later, Davies et al performed a transurethral resection of the prostate using the Puma 560.[12] This system eventually led to the development of PROBOT, a robot designed specifically for transurethral resection of the prostate. While PROBOT was being developed, Integrated Surgical Supplies Ltd. of Sacramento, CA, was developing ROBODOC, a robotic system designed to machine the femur with greater precision in hip replacement surgeries.[1] ROBODOC was the first surgical robot approved by the FDA.

Also in the mid-to-late 1980s a group of researchers at the National Air and Space Administration (NASA) Ames Research Center working on virtual reality became interested in using this information to develop telepresence surgery.[1] This concept of telesurgery became one of the main driving forces behind the development of surgical robots. In the early 1990s, several of the scientists from the NASA-Ames team joined the Stanford Research Institute (SRI). Working with SRI's other robotocists and virtual reality experts, these scientists developed a dexterous telemanipulator for hand surgery. One of their main design goals was to give the surgeon the sense of operating directly on the patient rather than from across the room. While these robots were being developed, general surgeons and endoscopists joined the development team and realized the potential these systems had in ameliorating the limitations of conventional laparoscopic surgery.

The US Army noticed the work of SRI, and it became interested in the possibility of decreasing wartime mortality by "bringing the surgeon to the wounded soldier—through telepresence."[1] With funding from the US Army, a system was devised whereby a wounded soldier could be loaded into a vehicle with robotic surgical equipment and be operated on remotely by a surgeon at a nearby Mobile Advanced Surgical Hospital (MASH). This system, it was hoped, would decrease wartime mortality by preventing wounded soldiers from exsanguinating before they reached the hospital. This system has been successfully demonstrated on animal models but has not yet been tested or implemented for actual battlefield casualty care.

Several of the surgeons and engineers working on surgical robotic systems for the Army eventually formed commercial ventures that lead to the introduction of robotics to the civilian surgical community.[1] Notably, Computer Motion, Inc. of Santa Barbara, CA, used seed money provided by the Army to develop the Automated Endoscopic System for Optimal Positioning (AESOP), a robotic arm controlled by the surgeon voice commands to manipulate an endoscopic camera. Shortly after AESOP was marketed, Integrated Surgical Systems (now Intuitive Surgical) of Mountain View, CA, licensed the SRI Green Telepresence Surgery system. This system underwent extensive redesign and was reintroduced as the Da Vinci surgical system. Within a year, Computer Motion put the Zeus system into production.

## CURRENT ROBOTIC SURGICAL SYSTEMS

Today, many robots and robot enhancements are being researched and developed. Schurr et al at Eberhard Karls University's section for minimally invasive surgery have developed a master-slave manipulator system that they call ARTEMIS.[13] This system consists of 2 robotic arms that are controlled by a surgeon at a control console. Dario et al at the

MiTech laboratory of Scuola Superiore Sant'Anna in Italy have developed a prototype miniature robotic system for computer-enhanced colonoscopy.[14] This system provides the same functions as conventional colonoscopy systems but it does so with an inchworm-like locomotion using vacuum suction. By allowing the endoscopist to teleoperate or directly supervise this endoscope and with the functional integration of endoscopic tools, they believe this system is not only feasible but may expand the applications of endoluminal diagnosis and surgery. Several other laboratories, including the authors', are designing and developing systems and models for reality-based haptic feedback in minimally invasive surgery and also combining visual servoing with haptic feedback for robot-assisted surgery.[15–19]

In addition to Prodoc, ROBODOC and the systems mentioned above several other robotic systems have been commercially developed and approved by the FDA for general surgical use. These include the AESOP system (Computer Motion Inc., Santa Barbara, CA), a voice-activated robotic endoscope, and the comprehensive master-slave surgical robotic systems, Da Vinci (Intuitive Surgical Inc., Mountain View, CA) and Zeus (Computer Motion Inc., Santa Barbara, CA).

The da Vinci and Zeus systems are similar in their capabilities but different in their approaches to robotic surgery. Both systems are comprehensive master-slave surgical robots with multiple arms operated remotely from a console with video assisted visualization and computer enhancement. In the da Vinci system (Fig. 1), which evolved from the telepresence machines developed for NASA and the US Army, there are essentially 3 components: a vision cart that holds a dual light source and dual 3-chip cameras, a master console where the operating surgeon sits, and a moveable cart, where 2 instrument arms and the camera arm are mounted.[1] The camera arm contains dual cameras and the image generated is 3-dimensional. The master console consists of an image processing computer that generates a true 3-dimensional image with depth of field; the view port where the surgeon views the image; foot pedals to control electrocautery, camera focus, instrument/camera arm clutches, and master control grips that drive the servant robotic arms at the patient's side.[6] The instruments are cable driven and provide 7 degrees of freedom. This system displays its 3-dimensional image above the hands of the surgeon so that it gives the surgeon the illusion that the tips of the instruments are an extension of the control grips, thus giving the impression of being at the surgical site.

The Zeus system is composed of a surgeon control console and 3 table-mounted robotic arms (Fig. 2). The right and left robotic arms replicate the arms of the surgeon, and the third arm is an AESOP voice-controlled robotic endoscope for visualization. In the Zeus system, the surgeon is seated comfortably upright with the video monitor and instrument handles positioned ergonomically to maximize dexterity and allow complete visualization of the OR environment. The system uses both straight shafted endoscopic instruments similar to conventional endoscopic instruments and jointed instruments with articulating end-effectors and 7 degrees of freedom.

## ADVANTAGES OF ROBOT-ASSISTED SURGERY

The advantages of these systems are many because they overcome many of the obstacles of laparoscopic surgery (Table 1). They increase dexterity, restore proper hand-eye coordination and an ergonomic position, and improve visualization (Table 2). In addition, these systems make surgeries that were technically difficult or unfeasible previously, now possible.

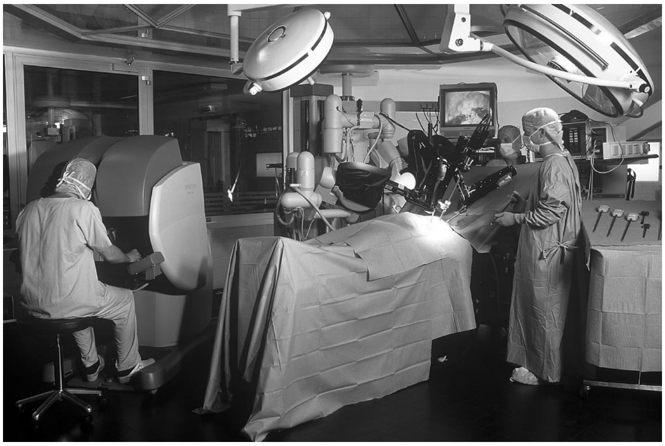

**FIGURE 1.** Da Vinci system set up. (Courtesy of Intuitive Surgical Inc., Mountain View, CA)

**FIGURE 2.** Zeus system set up. (Courtesy of Computer Motion Inc., Santa Barbara, CA)

 

**TABLE 1.** Advantages and Disadvantages of Conventional Laparoscopic Surgery Versus Robot-Assisted Surgery

| | Conventional Laparoscopic surgery | Robot-assisted surgery |
|---|---|---|
| Advantages | Well-developed technology | 3-D visualization |
| | Affordable and ubiquitous | Improved dexterity |
| | Proven efficacy | Seven degrees of freedom |
| | | Elimination of fulcrum effect |
| | | Elimination of physiologic tremors |
| | | Ability to scale motions |
| | | Micro-anastomoses possible |
| | | Tele-surgery |
| | | Ergonomic position |
| Disadvantages | Loss of touch sensation | Absence of touch sensation |
| | Loss of 3-D visualization | Very expensive |
| | Compromised dexterity | High start-up cost |
| | Limited degrees of motion | May require extra staff to operate |
| | The fulcrum effect | New technology |
| | Amplification of physiologic tremors | Unproven benefit |

These robotic systems enhance dexterity in several ways. Instruments with increased degrees of freedom greatly enhance the surgeon's ability to manipulate instruments and thus the tissues. These systems are designed so that the surgeons' tremor can be compensated on the end-effector motion through appropriate hardware and software filters. In addition, these systems can scale movements so that large movements of the control grips can be transformed into micromotions inside the patient.[6]

Another important advantage is the restoration of proper hand-eye coordination and an ergonomic position. These robotic systems eliminate the fulcrum effect, making instrument manipulation more intuitive. With the surgeon sitting at a remote, ergonomically designed workstation, current systems also eliminate the need to twist and turn in awkward positions to move the instruments and visualize the monitor.

By most accounts, the enhanced vision afforded by these systems is remarkable. The 3-dimensional view with depth perception is a marked improvement over the conventional laparoscopic camera views. Also to one's advantage is the surgeon's ability to directly control a stable visual field with increased magnification and maneuverability. All of this creates images with increased resolution that, combined with the increased degrees of freedom and enhanced dexterity,

**TABLE 2.** Advantages and Disadvantages of Robot-Assisted Surgery Versus Conventional Surgery

| Human strengths | Human limitations | Robot strengths | Robot limitations |
|---|---|---|---|
| • Strong hand–eye coordination | • Limited dexterity outside natural scale | • Good geometric accuracy | • No judgement |
| • Dexterous | • Prone to tremor and fatigue | • Stable and untiring | • Unable to use qualitative information |
| • Flexible and adaptable | • Limited geometric accuracy | • Scale motion | • Absence of haptic sensation |
| • Can integrate extensive and diverse information | • Limited ability to use quantitative information | • Can use diverse sensors in control | • Expensive |
| • Rudimentary haptic abilities | • Limited sterility | • May be sterilized | • Technology in flux |
| • Able to use qualitative information | • Susceptible to radiation and infection | • Resistant to radiation and infection | • More studies needed |
| • Good judgment | | | |
| • Easy to instruct and debrief | | | |

greatly enhances the surgeon's ability to identify and dissect anatomic structures as well as to construct microanastomoses.

## DISADVANTAGES OF ROBOT-ASSISTED SURGERY

There are several disadvantages to these systems. First of all, robotic surgery is a new technology and its uses and efficacy have not yet been well established. To date, mostly studies of feasibility have been conducted, and almost no long-term follow up studies have been performed. Many procedures will also have to be redesigned to optimize the use of robotic arms and increase efficiency. However, time will most likely remedy these disadvantages.

Another disadvantage of these systems is their cost. With a price tag of a million dollars, their cost is nearly prohibitive. Whether the price of these systems will fall or rise is a matter of conjecture. Some believe that with improvements in technology and as more experience is gained with robotic systems, the price will fall.[6] Others believe that improvements in technology, such as haptics, increased processor speeds, and more complex and capable software will increase the cost of these systems.[9] Also at issue is the problem of upgrading systems; how much will hospitals and healthcare organizations have to spend on upgrades and how often? In any case, many believe that to justify the purchase of these systems they must gain widespread multidisciplinary use.[9]

Another disadvantage is the size of these systems. Both systems have relatively large footprints and relatively cumbersome robotic arms. This is an important disadvantage in today's already crowded-operating rooms.[9] It may be difficult for both the surgical team and the robot to fit into the operating room. Some suggest that miniaturizing the robotic arms and instruments will address the problems associated with their current size. Others believe that larger operating suites with multiple booms and wall mountings will be needed to accommodate the extra space requirements of robotic surgical systems. The cost of making room for these robots and the cost of the robots themselves make them an especially expensive technology.

One of the potential disadvantages identified is a lack of compatible instruments and equipment. Lack of certain instruments increases reliance on tableside assistants to perform part of the surgery.[6] This, however, is a transient disadvantage because new technologies have and will develop to address these shortcomings.

Most of the disadvantages identified will be remedied with time and improvements in technology. Only time will tell if the use of these systems justifies their cost. If the cost of these systems remains high and they do not reduce the cost of routine procedures, it is unlikely that there will be a robot in every operating room and thus unlikely that they will be used for routine surgeries

## CURRENT CLINICAL APPLICATIONS AND EARLY DATA

Several robotic systems are currently approved by the FDA for specific surgical procedures. As mentioned previously, ROBODOC is used to precisely core out the femur in hip replacement surgery. Computer Motion Inc. of Goleta, CA, has 2 systems on the market. One, called AESOP, is a voice-controlled endoscope with 7 degrees of freedom. This system can be used in any laparoscopic procedure to enhance the surgeon's ability to control a stable image. The Zeus system and the Da Vinci system have been used by a variety of disciplines for laparoscopic surgeries, including cholecystectomies, mitral valve repairs, radical prostatectomies, reversal of tubal ligations, in addition to many gastrointestinal surgeries, nephrectomies, and kidney transplants. The number and types of surgeries being performed with robots is increasing rapidly as more institutions acquire these systems. Perhaps the most notable use of these systems, however, is in totally endoscopic coronary artery grafting, a procedure formerly outside the limitations of laparoscopic technology.

The amount of data being generated on robotic surgery is growing rapidly, and the early data are promising. Many studies have evaluated the feasibility of robot-assisted surgery. One study by Cadiere et al evaluated the feasibility of robotic laparoscopic surgery on 146 patients.[20] Procedures performed with a Da Vinci robot included 39 antireflux procedures, 48 cholecystectomies, 28 tubal reanastomoses, 10 gastroplasties for obesity, 3 inguinal hernia repairs, 3 intrarectal procedures, 2 hysterectomies, 2 cardiac procedures, 2 prostatectomies, 2 artiovenous fistulas, 1 lumbar sympathectomy, 1 appendectomy, 1 laryngeal exploration, 1 varicocele ligation, 1 endometriosis cure, and 1 neosalpingostomy. This study found robotic laparoscopic surgery to be feasible. They also found the robot to be most useful in intra-abdominal microsurgery or for manipulations in very small spaces. They reported no robot related morbidity. Another study by Falcone et al tested the feasibility of robot-assisted laparoscopic microsurgical tubal anastomosis.[31] In this study, 10 patients who had previously undergone tubal sterilization underwent tubal reanastomosis. They found that the 19 tubes were reanastomosed successfully and 17 of the 19 were still patent 6 weeks postoperatively. There have been 5 pregnancies in this group so far. Margossian and Falcone also studied the feasibility of robotic surgery in complex gynecologic surgeries in pigs.[22] In this study, 10 pigs underwent adnexal surgery or hysterectomy using the Zeus robotic system. They found that robotic surgery is safe and feasible for complex gynecologic surgeries. In yet another study by Marescaux et al, the safety and feasibility of telerobotic laparoscopic cholecystectomy was tested in a prospective study of 25 patients undergoing the procedure.[33] Twenty-four of the 25 laparoscopic cholecystectomies were performed successfully, and one was converted to a traditional laparoscopic procedure. This study concluded that robotic laparoscopic cholecystectomy is safe and feasible. Another study by Abbou et al found telerobotic laparoscopic radical prostatectomy to be feasible and safe with dramatically enhanced dexterity.[34]

One of the areas where robotic surgery is transforming medicine the most and one of the areas generating the most excitement is minimally invasive cardiac surgery. Several groups have been developing robotic procedures that expand laparoscopic techniques into this previously unexplored territory with encouraging results. Prasad et al successfully constructed left internal thoracic artery (LITA) to left anterior descending (LAD) artery anastomoses on 17 of 19 patients with the use of a robotic system.[21] They conclude that robotically assisted endoscopic coronary bypass surgery showed favorable short-term outcomes with no adverse events and found robotic assistance is an enabling technology that allows surgeons to perform endoscopic coronary anastomoses. Damiano et al conducted a multicenter clinical trial of robotically assisted coronary artery bypass grafting.[35] In this study 32 patients scheduled for primary coronary surgery underwent endoscopic anastomosis of the LITA to LAD. Two-month follow-up revealed a graft patency of 93%. This study concluded that robotic assisted coronary bypass grafting is feasible. In another study, Mohr et al used the Da Vinci system to perform coronary artery bypass grafting on 131 patients and mitral valve repair on 17 patients.[21] They used the robot to perform left internal thoracic artery takedown, LITA-LAD anastomosis in standard sternotomy bypass, and total endoscopic coronary artery bypass grafting LITA-LAD anastomosis on the arrested heart and the beating heart. They found that robotic systems could be used safely in selected patients to perform endoscopic cardiac surgery. Internal thoracic artery takedown is an effective modality, and total endoscopic bypass on an arrested heart is feasible but does not offer a major benefit to the minimally invasive direct approach because cardiopulmonary bypass is still required. Their study suggests that robotic systems have not yet advanced far enough to perform endoscopic closed chest beating heart bypass grafting despite some technical success in 2 of 8 patients. In addition, robotic endoscopic mitral valve repair was successful in 14 of 17 patients. In contrast, several groups in Europe have successfully performed closed- chest, off-pump coronary artery bypass grafting using an endoscopic stabilizer. Kappert and Cichon et al performed 37 off-pump totally endoscopic coronary artery bypass (TECAB) on a beating heart with the Da Vinci system and an endoscopic stabilizer.[32] In this series, they reported a 3.4% rate of conversion to median sternotomy. They concluded that their results promote optimism about further development of TECAB. Another study by Boehm and Reichenspurner et al using a similar stabilizer with the Zeus system had similar results and conclusions about TECAB.[33] Interestingly, a study by Cisowski and Drzewiecki in Poland compared percutaneous stenting with endoscopic coronary artery bypass grafting in patients with single-vessel disease. In this series of 100 patients percutaneous stenting resulted in restenosis in 6% and 12% at 1 and 6 months, respectively, compared with 2% at 6 months in the endoscopic bypass group.[34]

Another use for robotic systems being investigated is pediatric laparoscopic surgery. Currently, laparoscopic pediatric surgery is limited by an inability to perform precise anastomoses of 2 to 15 millimeters.[35] Although laparoscopic techniques may be used to treat infants with intestinal atresia, choledochal cysts, biliary atresia, and esophageal atresia, it is not the standard approach because of the technical difficulties. To evaluate the feasibility of robotic systems in pediatric minimally invasive surgery, Hollands and Dixey developed a study where enteroenterostomy, hepaticojejunostomy, and portoentorostomy were performed on piglets.[30] They found all the procedure to be technically feasible with the Zeus robotic system. The study concludes that robotic-assisted laparoscopic techniques are technically feasible in pediatric surgery and may be of benefit in treating various disorders in term and preterm infants. More recently, Hollands and Dixey devised a study using 10 piglets to develop the procedure and evaluate the feasibility of performing a robot-assisted esophagoesophagostomy. In this study, robot-assisted and thoracoscopic approaches were evaluated and compared for leak, narrowing, caliber, mucosal approximation, as well as anesthesia, operative, anastomotic, and robotic set-up times. They found that the robot-assisted approach is feasible. They also discerned no statistically significant difference between the 2 approaches based on the above variables.[31]

Despite many studies showing the feasibility of robotic surgery, there is still much to be desired. More high-quality clinical trials need to be performed and much more experience needs to be obtained before the full potential of these systems can be realized.

## PRACTICAL USES OF SURGICAL ROBOTS TODAY

In today's competitive healthcare market, many organizations are interested in making themselves "cutting-edge" institutions with the most advanced technological equipment and the very newest treatment and testing modalities. Doing so allows them to capture more of the healthcare market. Acquiring a surgical robot is in essence the entry fee into marketing an institution's surgical specialties as "the most advanced." It is not uncommon, for example, to see a photo of a surgical robot on the cover of a hospital's marketing brochure and yet see no word mentioning robotic surgery inside.

As far as ideas and science, surgical robotics is a deep, fertile soil. It may come to pass that robotic systems are used very little but the technology they are generating and the

**TABLE 3.** Current Applications of Robotic Surgery

| Orthopedic surgery | Neurosurgery | Gynecologic surgery | Cardiothoracic surgery | Urology | General surgery |
|---|---|---|---|---|---|
| Total hip arthroplasty: femur preparation | Complement image-guided-surgery | Tubal re-anastomosis | Mammary artery harvest | Radical prostatectomy | Cholecystectomy |
| Total hip arthroplasty: acetabular cup placement | Radiosurgery | Hysterectomies | CABG | Ureter repair | Nissen fundoplication |
| Knee surgery | | Ovary resection | Mitral valve repair | Nephrectomy | Heller myotomy |
| Spine surgery | | | | | Gastric bypass |
| | | | | | Adrenalectomy |
| | | | | | Bowel resection |
| | | | | | Esophagectomy |

advances in ancillary products will continue. Already, the development of robotics is spurring interest in new tissue anastomosis techniques, improving laparoscopic instruments, and digital integration of already existing technologies.

As mentioned previously, applications of robotic surgery are expanding rapidly into many different surgical disciplines. The cost of procuring one of these systems remains high, however, making it unlikely that an institution will acquire more than one or two. This low number of machines and the low number of surgeons trained to use them makes incorporation of robotics in routine surgeries rare. Whether this changes with the passing of time remains to be seen.

## THE FUTURE OF ROBOTIC SURGERY

Robotic surgery is in its infancy. Many obstacles and disadvantages will be resolved in time and no doubt many other questions will arise. Many question have yet to be asked; questions such as malpractice liability, credentialing, training requirements, and interstate licensing for tele-surgeons, to name just a few.

Many of current advantages in robotic assisted surgery ensure its continued development and expansion. For example, the sophistication of the controls and the multiple degrees of freedom afforded by the Zeus and da Vinci systems allow increased mobility and no tremor without comprising the visual field to make micro anastomosis possible. Many have made the observation that robotic systems are information systems and as such they have the ability to interface and integrate many of the technologies being developed for and currently used in the operating room.[9] One exciting possibility is expanding the use of preoperative (computed tomography or magnetic resonance) and intraoperative video image fusion to better guide the surgeon in dissection and identifying pathology. These data may also be used to rehearse complex procedures before they are undertaken. The nature of robotic systems also makes the possibility of long-distance intraoperative consultation or guidance possible and it may provide new opportunities for teaching and assessment of new surgeons through mentoring and simulation. Computer Motion, the makers of the Zeus robotic surgical system, is already marketing a device called SOCRATES that allows surgeons at remote sites to connect to an operating room and share video and audio, to use a "telestrator" to highlight anatomy, and to control the AESOP endoscopic camera.

Technically, much remains to be done before robotic surgery's full potential can be realized. Although these systems have greatly improved dexterity, they have yet to develop the full potential in instrumentation or to incorporate the full range of sensory input. More standard mechanical tools and more energy directed tools need to be developed. Some authors also believe that robotic surgery can be extended into the realm of advanced diagnostic testing with the development and use of ultrasonography, near infrared, and confocal microscopy equipment.[10]

Much like the robots in popular culture, the future of robotics in surgery is limited only by imagination. Many future "advancements" are already being researched. Some laboratories, including the authors' laboratory, are currently working on systems to relay touch sensation from robotic instruments back to the surgeon.[15–19,32] Other laboratories are working on improving current methods and developing new devices for suture-less anastomoses.[33–35] When most people think about robotics, they think about automation. The possibility of automating some tasks is both exciting and controversial. Future systems might include the ability for a surgeon to program the surgery and merely supervise as the robot performs most of the tasks. The possibilities for improvement and advancement are only limited by imagination and cost.

## CONCLUSION

Although still in its infancy, robotic surgery has already proven itself to be of great value, particularly in areas inaccessible to conventional laparoscopic procedures. It remains to be seen, however, if robotic systems will replace conventional laparoscopic instruments in less technically demanding procedures. In any case, robotic technology is set to revolutionize surgery by improving and expanding laparoscopic procedures, advancing surgical technology, and bringing surgery into the digital age. Furthermore, it has the potential to expand surgical treatment modalities beyond the limits of human ability. Whether or not the benefit of its usage overcomes the cost to implement it remains to be seen and much remains to be worked out. Although feasibility has largely been shown, more prospective randomized trials evaluating efficacy and safety must be undertaken. Further research must evaluate cost effectiveness or a true benefit over conventional therapy for robotic surgery to take full root. Table 3.

## REFERENCES


1. Satava RM. Surgical robotics: the early chronicles: a personal historical perspective. *Surg Laparosc Endosc Percutan Tech*. 2002;12:6–16.
2. Felger JE, Nifong L. The evolution of and early experience with robot assisted mitral valve surgery. *Surg Laparosc Endosc Percutan Tech*. 2002;12:58–63.
3. Marescaux J, Leroy J, Rubino F, et al. Transcontinental robot-assisted remote telesurgery: feasibility and potential applications. *Ann Surg*. 2002;235:487–492.
4. Cheah WK, Lee B, Lenzi JE, et al. Telesurgical laparoscopic cholecystectomy between two countries. *Surg Endosc*. 2000;14:1085.
5. Jones SB, Jones DB. Surgical aspects and future developments in laparoscopy. *Anesthiol Clin North Am*. 2001;19:107–124.
6. Kim VB, Chapman WH, Albrecht RJ, et al. Early experience with telemanipulative robot-assisted laparoscopic cholecystectomy using Da Vinci. *Surg Laparosc Endosc Percutan Tech*. 2002;12:34–40.
7. Fuchs KH. Minimally invasive surgery. *Endoscopy*. 2002;34:154–159.
8. Allendorf JD, Bessler M, Whelan RL, et al. Postoperative immune function varies inversely with the degree of surgical trauma in a murine model. *Surg Endosc*. 1997;11:427–430.
9. Satava RM, Bowersox JC, Mack M, et al. Robotic surgery: state of the art and future trends. *Contemp Surg*. 2001;57:489–499.
10. Prasad SM, Ducko CT, Stephenson ER, et al. Prospective clinical trial of robotically assisted endoscopic coronary grafting with 1 year follow-up. *Ann Surg*. 2001;233:725–732.
11. Kwoh YS, Hou J, Jonckheere EA, et al. A robot with improved absolute positioning accuracy for CT guided stereotactic brain surgery. *IEEE Trans Biomed Eng*. 1988;35:153–161.
12. Davies B. A review of robotics in surgery. *Proc Inst Mech Eng*. 2000;214:129–140.
13. Schurr MO, Buess GF, Neisius B, et al. Robotics and telemanipulation technologies for endoscopic surgery: a review of the ARTEMIS project. Advanced robotic telemanipulator for minimally invasive surgery. *Surg Endosc*. 2000;14:375–381.
14. Dario P, Corrozza MC, Peitrabissa A. Development and in vitro testing of a miniature robotic system for computer-assisted colonoscopy. *Comput Aided Surg*. 1999;4:1–14.
15. Tholey G, Chanthasopeephan T, Hu T, et al. Measuring Grasping and Cutting Forces for Reality-Based Haptic Modeling. Computer Assisted Radiology and Surgery, 17th International Congress and Exhibition, June 2003, London, UK.
16. Hu T, Castellanos A, Tholey G, et al. Real-Time Haptic feedback Laparoscopic tool for use in Gastro-intestinal Surgery. Fifth International Conference on Medical Image Computing and Computer Assisted Intervention (MICCAI), Tokyo, Japan, September 2002.
17. Kennedy C, Hu T, Desai JP, et al. A Novel Approach to Robotic Cardiac Surgery using Haptics and Vision. Cardiovascular Engineering: An International Journal, 2002.
18. Kennedy C, Hu T, Desai JP. Combining Haptic and Visual Servoing for Cardiothoracic Surgery. *2002 IEEE International Conference on Robotics and Automation*, Volume: 2, 2002 Page(s): 2106–2111, Washington DC, May 2002.
19. Kennedy CW, Desai JP. Force Feedback Using Vision. The 11th International Conference on Advanced Robotics, June 30–July 3, 2003 University of Coimbra, Portugal.
20. Cadierre GB, Himpens J. Feasibility of robotic laparoscopic surgery: 146 cases. *World J Surg*. 2001;25:1467–1477.
21. Falcone T, Goldberg JM, Margossian H, et al. Robotic-assisted laparoscopic microsurgical tubal anastomosis: human pilot study. *Fertil Steril*. 2000;73:1040–1042.
22. Margossian H, Falcone T. Robotically assisted laparoscopic hysterectomy and adnexal surgery. *J Laparoendosc Adv Surg Tech A*. 2001;11:161–165.
23. Marescaux J, Smith MK, Folscher D, et al. Telerobotic laparoscopic cholecystectomy: initial clinical experience with 25 patients. *Ann Surg*. 2001;234:1–7.
24. Abbou CC, Hoznek A, Saloman L, et al. Laparoscopic radical prostatectomy with a remote controlled robot. *J Urol*. 2001;165:1964–1966.
25. Damiano RJJr, Tabaie HA, Mack MJ, et al. Initial multicenter clinical trial of robotically assisted coronary artery bypass grafting. *Ann Thorac Surg*. 2001;72:1263–1268.
26. Mohr FW, Falk V, Diegeler A, et al. Computer-enhanced "robotic" cardiac surgery: experience in 148 patients. *J Thorac Cardiovasc Surg*. 2001;121:842–853.
27. Kappert U, Cichon R, Schneider J, et al. Technique of closed chest coronary artery surgery on the beating heart. *Eur J Cardiothorac Surg* 2001;20:765–769.
28. Boehm DH, Reichenspurner H, Gulbins H, et al. Early experience with robotic technology for coronary artery surgery. *Ann Thorac Surg*. 1999;68:1542–1546.
29. Cisowski M, Drzewiecki J, Drzewiecka-Gerber A, et al. Primary stenting versus MIDCAB: preliminary report-comparison of two methods of revascularization in single left anterior descending coronary artery stenosis. *Ann Thorac Surg*. 2002;74:S1334–S1339.
30. Hollands CM, Dixey LN. Technical assessment of porcine enteroenterostomy performed with Zeus robotic technology. *J Pediatr Surg*. 2001;36:1231–1233.
31. Hollands CM, Dixey LN. Robot-assisted eophagoesophagostomy. *J Pediatr Surg*. 2002;37:983–985.
32. Morimoto AK, Foral RD, Kuhlman JL, et al. Force Sensor for laparoscopic babcock. *Stud Health Technol Inform*. 1997;39:354–361.
33. Tozzi P, Corno A, von Segesser L. Sutureless coronary anastomoses: revival of old concepts. *Eur J Cardiothoracic Surg*. 2002;22:565.
34. Buijsrogge MP, Scheltes JS, Heikens M, et al. Sutureless coronary anastomosis with an anastomotic device and tissue adhesive in off-pump porcine coronary bypass grafting. 2002;123:788–794.
35. Eckstein FS, Bonilla LF, Schaff H, et al. Two generations of the St. Jude Medical ATG coronary connector systems for coronary artery anastomosis in coronary artery bypass grafting. *Ann Thorac Surg*. 2002;74:S1363–S1367.