

Robotics

Revolutionizing urologic surgery

By Dan Stoianovici, PhD

To many, the idea of computer-driven robots performing surgery seems fantastic, bringing to mind the “mecha”racters from Steven Spielberg’s recent science fiction movie *AI*. In reality, however, a number of robotic systems have been evaluated in clinical

their robotic systems—the organs that were to be operated on could be immobilized and had reduced deformability. Conversely, systems used for soft tissue operations, such as those performed in urology, require very sophisticated robotic responsiveness and computer control

are 2 clear advantages that robots offer over humans: the ability to operate based on digital information, which permits precise image-based targeting; and outstanding motion capabilities, which allows for improved, minimally invasive access. To date, however, computer vision and image interpretation remain major limiting factors.

Though not yet commonplace, robotic systems are appearing with increasing frequency in the operating room and are gaining wider acceptance by the surgical community. An examination of the current state of robotics in urology shows its ability to improve existing operative techniques and its promise for future advances.

How they work

Robots are mechanical systems that are controlled by microprocessors and are equipped with sensors and motors. Computer algorithms use the environmental information provided by the sensors and the input of the operator to impose appropriate motor commands, enabling the mechanical system to perform a desired task. In surgical robotics, a task can be predefined by the surgeon based on preoperative or interventional data, or it can be defined at surgery when, due to its complexity, the dynamics of the task cannot be set prior to the operation. There are 2 main categories of surgical robots: image-guided and surgeon-driven systems.

Image-guided robotic systems

These systems are used in radiologic interventions (such as percutaneous needle access) to guide and,

trials, and some—having demonstrated their clinical utility and ability to enhance surgical performance—have received Food and Drug Administration (FDA) approval and are now commercially available.

Unfortunately, urologic surgeons have not embraced robots as enthusiastically as their colleagues in orthopedics and neurosurgery—or even cardiology.¹ Although orthopedic surgeons and neurosurgeons pioneered the use of surgical robotics in the 1980s, they had the advantage of having simpler requirements for

awareness to adapt to the deformability and mobility of the organs. While these difficulties delayed the progress of urology robotics (URobotics), several systems applicable to urology, including surgeon-driven robots and robots developed specifically for urologic applications, have nonetheless been developed or are currently under development.

As “mechatronic” technology advances, the capabilities of surgical robots are evolving as well, enabling them to perform less invasive procedures with increasing autonomy. Driving this technology

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Under a licensing agreement between ImageGuide Inc. and the Johns Hopkins University, Dr. Stoianovici is entitled to a share of royalty received by the University on sales of the RCM and Tracker robots described in this article. Dr. Stoianovici and the University are also shareholders in ImageGuide Inc.

sometimes, to insert an instrument or probe into the body. These systems typically act as trajectory-enforcement devices that are used in conjunction with C-arm and biplanar fluoroscopy, ultrasonography (US), or computed tomography (CT) and magnetic resonance imaging (MRI) scanners.² Image-guided systems take advantage of the robot's ability to use digital coordinate information provided by the imager to manipulate instruments in the physical space of the patient. This type of instrument manipulation can be accomplished with greater accuracy than manual placement using image-space feedback.

The first purpose-built, image-guided robot for urology was introduced in 1989 by a group at The Imperial College in London.³ It was designed to perform transurethral resection of the prostate because of the relatively fixed position of the prostate and because the procedure requires the performance of repetitive movements in a geometric pattern.^{3,4} In 5 clinical trials, the robot automatically generated a sequence of overlapping cuts in successively larger rings, starting at the hypothetical bladder neck. Trials identified that, at that time, US was insufficiently accurate for robot control.^{5,6} Although not absolutely successful, this system was the first recorded autonomous robotic surgery in humans—and the first URobot.

X-ray guidance. The group at The Imperial College also created a robotic system to assist with intraoperative percutaneous renal access.⁷ They employed a passive encoded arm equipped with electromagnetic

FIGURE 1
PAKY-RCM robot



The needle in the driver can be oriented and inserted robotically under C-arm guidance.

brakes mounted to the operating table. The access needle was manually positioned as prescribed by a computer that triangulated the calyceal location from multiple C-arm x-rays.⁸ In vitro experiments evaluating system performance demonstrated its accuracy, positioning the needle less than 1.5 mm from the target.

In 1996, the URobotics program at Johns Hopkins in Baltimore also developed a robotic module for percutaneous access of the kidney (PAKY).⁹ This module is an active and radiolucent needle driver, which was initially supported by a passive arm.¹⁰ The needle in the driver was manually positioned under C-arm guidance, and once locked in place, needle insertion was performed automatically by a surgeon controlling a joystick. PAKY has been used successfully in numerous clinical cases, although the procedure essentially remained manually guided.¹¹ The main advantage of PAKY was that it held the needle and locked its trajectory, allowing the surgeon's hands to remain out of the x-ray field during insertion.

Needle orientation was automated with the addition of the remote center of motion (RCM) module (ImageGuide Inc, Baltimore, Md), which supports and orients the PAKY driver while maintaining the fixed location of the needle tip (Figure 1).¹² Known as PAKY-RCM, this system allows for robotic orientation and insertion of the needle using various x-ray guidance procedures. The system, which has been used extensively for percutaneous renal access at Johns Hopkins, offers improved needle

placement accuracy, a shortened procedure time, and reduced radiation exposure to the patient and the urologist.¹¹ PAKY-RCM can integrate C-arm software and uses "Fluoro-Serving" image registration and guidance software to automatically place the needle at the targeted image, which is pointed to by the urologist using a mouse.¹³ The PAKY-RCM has been used in several transatlantic telesurgical cases.¹⁴

CT-guidance. A simple method for robot registration, laser-based CT/MR registration, was also developed in our URobotics laboratory to allow the PAKY-RCM system to be used under CT guidance.¹⁵ The registration method uses the laser markers readily available on any CT scanner and does not require the surgeon to be adjacent to the patient, thus eliminating radiation exposure. The system (Figure 2) has been used successfully for multiple CT-guided biopsy and radiofrequency (RF) ablation procedures on the kidney and spine and for nephrostomy tube placement.¹⁶

Tracker (ImageGuide Inc), our most recent robotic system, was

specifically developed for CT-guided percutaneous procedures (Figure 3).¹⁷ Its name was derived from its ability to actively track respiratory and other soft tissue motion. Tracker can precisely manipulate needles and other surgical instruments in the confined space of the imager without interfering with image quality.

Tracker is connected to the mobile table of the CT, allowing the patient and the robot to be sent together into the CT gantry for imaging and interventional procedures. The system is composed of the PAKY and RCM robotic modules, a new passive positioning arm, and a translational stage, which allows an active 3 degrees of freedom (DOF), all mounted on a bridge-like support. A touch-screen display and a joystick are mounted on the robot. Investigators at Georgetown Medical Center in Washington, DC, will soon begin clinical evaluation of the Tracker system.

US guidance. Another image-guided robot that has been evaluated clinically was developed at the Politecnico of Milan, Italy to perform transperineal prostate biopsies.^{17,18} Using transrectal US (TRUS), this system can accurately position the needle within 1 to 2 mm of the target. With this system, the surgeon chooses the biopsy site from the TRUS images, and the robot obtains the sample. While the robot demonstrated increased accuracy compared with the manual procedure, broad clinical use of this system has been limited due to increased set-up time and expense.

A system that performs prostate brachytherapy under TRUS guid-

FIGURE 2

PAKY-RCM robot in CT-guided nephrostomy tube placement



Laser-based CT/MR registration allows the PAKY-RCM system to be used under CT guidance.

ance is also under development, and an evaluation on phantom models was considered successful.¹⁹

MR guidance. The development of an MR-compatible robotic system is at the forefront of image-guided research. Hynynen and colleagues developed an MR-guided system for noninvasive surgery with high-intensity focused ultrasound (HIFU).²⁰ Masamune and colleagues

at the University of Tokyo developed an MR-compatible needle insertion manipulator using ultrasonic actuation and tested it on phantom models.²¹ Researchers at the Brigham and Women's Hospital in Boston, in collaboration with the Agency for Industrial Science and Technology/Ministry of International Trade and Industry in Japan, are developing a novel system composed of a 5-DOF manipulator and a "double donut" open MR scanner.²² The robot is located between the vertical donuts above the surgeon's

head and presents 2 long arms that extend into the imaging region close to the patient. The system is designed to serve as an image-guided surgical assistant, integrating preoperative planning and intraoperative MRI.

MicRo, a multi-imager compatible robot under development in our laboratory, is designed to help obtain precise percutaneous prostate

FIGURE 3

Tracker robot mounted on CT scanner



Left: Touch-screen controller. Right: Robot, consisting of RCM modules, a passive positioning arm, and an XYZ translational stage, all mounted on a bridge-like support. This system was specifically developed for CT-guided percutaneous procedures.

FIGURE 4

SRI teleoperation system for open surgical procedures



This surgeon-driven instrument manipulation system, which was designed for open surgical procedures, includes a 2-arm, high-mobility robot instrumented with grippers.

FIGURE 5

daVinci robotic system



Left: The daVinci robotic system consists of a 3-arm robotic unit. Right: Surgeon-operated control console.

access for minimally invasive therapies. This robot has a novel MR-compatible motor that uses hydraulic energy.

Surgeon-driven robotic systems

These systems comprise specialized input devices from which the surgeon directly controls the motion

of the instruments manipulated by the robot. In robotics terminology, this is referred to as master-slave system architecture. These systems combine the fine manipulation capabilities of a robotic system with the surgeon's perception and judgment, allowing for scaled down, steady, tremor-free motion. The surgeon is located away from the operative field, which permits access to confined spaces during minimally invasive procedures and offers the ability to perform telesurgical procedures.²³

Most surgeon-driven robotic systems have been created for general laparoscopic use. They include manipulator arms that help the surgeon increase manual dexterity and perform tasks such as positioning the laparoscope.

AESOP. The first surgical robot to receive FDA clearance was the Automated Endoscopic System for Optimal Positioning (AESOP, Computer Motion Inc, Goleta, Calif). AESOP is one of the simplest types of surgeon-driven systems because its only function is to hold and orient a laparoscopic camera under hand, foot, or voice control. The robot has been used at several institutions and in many clinical areas, including urologic laparoscopy.²⁴ Kavoussi and associates found that the camera was significantly steadier under robot control, and neither operative set-up nor breakdown time was increased with the use of the robotic assistant.²⁵

SRI. The first surgeon-driven instrument manipulation system was developed at the Stanford Research Institute (SRI) in Menlo Park, Calif for use during open surgical procedures. This system, which is operated from a console, includes a 2-arm, high-mobility ro-

bot instrumented with grippers (Figure 4). Cornum and Bowersox used the system for in vivo porcine nephrectomy and the repair of bladder and urethral injuries.²⁶

daVinci. Perhaps the most successful surgical robot today is the "daVinci" laparoscopic robot system (Intuitive Surgical Inc, Mountain View, Calif). Like the SRI robot, this system (Figure 5) has a control console that is operated by the surgeon and a 3-arm robotic unit (2 arms for instrument manipulation and 1 for the laparoscope). Pencil-sized instruments, such as needle holders, scissors, dissectors, and scalpel, are equipped with a wrist to provide additional dexterity.²⁷ Several European centers have used daVinci to perform laparoscopic cardiac bypass surgery without cardiopulmonary bypass. The daVinci system received FDA clearance in 2001 and is presently being used in most major clinical centers across the country. The range of uses for the daVinci system includes a number of urologic applications and is constantly expanding.

Zeus. The most successful telesurgical operation to date was "Operation Lindbergh," which was performed in September 2001 using the Zeus robotic system (Computer Motion Inc) for laparoscopic sur-

FIGURE 6
Zeus robotic system



A bilateral console allows the surgeon to operate the Zeus system.

gery. The surgeon, who was in New York, performed a laparoscopic gall bladder operation on a patient in Strasbourg, France. The Zeus system, which can also be operated locally, consists of 3 modified AESOP robots—1 for the laparoscope and 2 for the instruments—and a bilateral surgeon's console (Figure 6). The system has not yet received FDA approval. Compared with daVinci, Zeus requires significantly less preoperative setup. However, Zeus is currently less

maneuverable than daVinci. This is primarily because Zeus uses AESOP robots originally designed for camera holding, while daVinci was purposely designed for a master-slave operation.

Conclusion

Surgical robotics opens wide the possibility of improving existing operative techniques and performing new procedures. Among many other advantages, robots allow for more precise manipulation of surgical instruments compared with manual procedures. Digital mapping of the patient by sophisticated imaging equipment can allow for autonomous control.

Several surgical robots have been developed and tested, and some have demonstrated clinical utility. With continued hardware and software improvements, the applications for surgical robotics will only expand, opening new horizons for urologic practice.

Acknowledgement

Some of the work presented was partially supported by grant No. 1R21CA088232-01A1 from the National Cancer Institute (NCI). This article's contents are solely the responsibility of the authors and do not necessarily represent the official views of NCI.

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