Robotic Tools for Minimally Invasive Urologic Surgery

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1. Introduction:

Surgical robots have begun to appear on the market in the last few years and have started to populate the operating rooms in large medical centers. These systems have already established their ability to augment a surgeon's dexterity in minimally invasive procedures and have the potential to maximize patient outcome on a larger basis even though, for the moment, their cost is prohibitively high for widespread application. As surgeons become increasingly aware of the clinical benefits of these systems and costs are driven down by technological advance and availability, we foresee that robots will become standard operating room tools. Initial applications of a handful of robots have already demonstrated their surgical potential. As technology evolves, robots could not only improve performance in minimally invasive procedures, but also enhance other existing procedures or even enable entirely new kinds of surgeries.

This chapter outlines the current aptitudes and limitations of several commercial and research surgical robots. Local and telesurgical systems and procedures are discussed together with a forecast of future development. We begin with an overview of surgical robotic technology, terminology and classification, as well as the short history of their evolution, highlighting the potential of these systems, before proceeding to discuss several specific surgical systems.

2. Overview of Surgical Robotics

Computer integrated surgical systems are a new class of "intelligent" surgical tools which may include surgical robots. The robotic manipulator itself is just one element of a larger system that includes preoperative planning based on medical images, intraoperative registration (matching the patient to the pre-surgical images) and a combination of robotically assisted and manually controlled tools for carrying out the plan, as well as patient verification and follow-up.

The chief advantages of robotic manipulation of surgical tools are generally a) accurate registration to medical images; b) consistent movement free of fatigue and tremor; c) the ability to work in imaging environments unfriendly to human surgeons; and d) the ability to reposition instruments quickly and accurately through complex trajectories or onto multiple targets.

In surgical robotics the task may either be predefined by the surgeon based on preoperative / interventional data or, for more complex procedures, be defined as the surgery progresses in the operating room. Based on this distinction, surgical robots may be classified into two main groups: Image-Guided and Surgeon-Driven systems. These categories both make use of the complementary skills/advantages of surgeon and robot, but they do so in different ways.

Image-Guided robotic systems excel at precisely reaching a target specified by the surgeon. In radiological interventions such as percutaneous needle access, these systems are used to guide and sometimes to insert a needle, instrument or probe. Their purpose is to act as a trajectory-enforcement device, correctly aligning the needle based on images from ultrasound, C-Arm or biplanar fluoroscopy units, CT or even MRI scanners [1]. Image-guided systems take advantage of the capability of robotic systems to register the medical image to the patient more easily and accurately than humans can. The robot can then precisely manipulate instruments to reach the locations in the patient space that are selected in the medical image. The system complements the planning and decision-making skills of the surgeon by actualizing his intention.

With surgeon-driven robots, the surgeon directly controls the motion of the instruments held by the robot. These systems combine the fine manipulation capabilities of robotic systems with the surgeon's perception and judgment, performing scaled down, steady, tremor-free motion. These robots enable increased resolution of movement and vision, and make laparoscopic tools more dexterous. The laparoscopic robot "hands" emulate the movement capability of human hands and wrists much better than traditional laparoscopic tools. Additionally, robotic systems can fuse radiographic and three-dimensional data to real-time surface data, providing better visualization of the target tissue or structures that need to be avoided.

When performing surgery with a robotic system, the surgeon is often located distal to the operating field. Robotic tools allow easier access to confined spaces in minimally invasive procedures and also enable the doctor to be at a distance from the patient and, thus, perform telesurgery [2]. Future developments may allow the computer to sense joint and muscle movements in the operator's hands, arms, head and neck, and to respond accordingly. A prototype system currently under development senses the electrical signals in the operator's biceps, and flexes or extends a robotic arm accordingly [3]. Increased public demand for minimally invasive surgery is not being satisfied by a sufficient number of experienced, qualified surgeons [4]. Telemedicine provides the unique advantage of allowing specialists in remote locations to assist and train local surgeons. Robotic tools enable the remote surgeon not only to offer advice, but to participate directly in the operation. This has been successfully done inter-continentally, as will be described later.

Robotic systems have profound implications when applied to training. Robotic and computer training simulations can enable some surgical training activities to be carried out in virtual reality or simulated environments without risk and/or harm to an animal or human patient. Further, these devices may one day allow surgical learning progress to be measured quantitatively and tracked over time.

Robotic surgery is a fascinating and quickly evolving field of medicine as doctors and engineers collaborate to develop innovative new procedures and the technology that makes them possible. While patients will grow to appreciate the accuracy of robots, they will always want the judgment of a human doctor in control of the robot. Robotic technology will never replace the doctor, but it represents a new type of tool with promising capabilities.

2. History of Urologic Robots:

Robotic-assisted devices in medicine were first used in rehabilitation before making their way into the operating room [5]. Surgical robotics pioneered in the 1980s in the fields of orthopedics and neurosurgery with predefined-task robots [6]. Urology robotics ("URobotics") was slower to develop because it is more difficult to build robots to operate on soft tissue organs due to their higher deformability and mobility. Although these difficulties delayed URobotics development, innovative research has produced several systems either applicable to, or purposely designed for, urology.

The first URobot was the PROBOT, introduced in 1989 by a group at the Imperial College in London for performing robot-assisted transurethral resection of the prostate (TURP) [7, 8]. The robot serially cored the periurethral prostatic tissue, while hemostasis was achieved manually using electrocautery after completion of the tissue resection. The device never achieved widespread use; however, since then, many minimally invasive techniques for the treatment of benign prostatic hyperplasia have been introduced. This would seem to indicate a desire to replace the standard TURP by a less invasive strategy. Transrectal ultrasound (TRUS) is used in many of these new techniques for intraoperative monitoring and image-guided robot assistance.

In 1994, Potamianos et al. investigated a robotic system to assist the urologist with intraoperative percutaneous renal access [9]. They employed a passive, encoded arm equipped with electromagnetic brakes, mounted onto the operating table. The access needle was manually positioned as prescribed by a computer, which triangulated the calyx location from multiple C-arm X-rays [10]. In vitro experiments evaluating system performance demonstrated a targeting accuracy of less than 1.5 mm.

In 1995, a research group headed by Russell Taylor at IBM developed the Remote Center of Motion (RCM) concept and implemented it on the LARS robot [11, 12]. The RCM is a component of nearly all medical robotic systems today and is described in the next section. Subsequently, LARS was used in our institution for experimental percutaneous renal access [13]. These experiments revealed areas for improvement and led our URobotics research group to create the PAKY-RCM (Percutaneous Access of the Kidney) robot [14]. These systems are further described in the Image-Guided Robotics section.

The use of robots in laparoscopy is yet another direction in the evolution of minimally invasive techniques and has been successfully applied in several centers in Europe and the USA. The first robots used to control laparoscopic tools in urologic surgery were manipulator arms such as the Automated Endoscopic System for Optimal Positioning (AESOP™ - Computer Motion, Inc., Goleta, CA.). Such laparoscopic systems are quite recent, having been developed in the late 1990s and cleared by the FDA within the past few years. This type of robot, among others, is described later in the Surgeon-Driven Robots section.

The entire history of robots in surgery is rather contemporary; however, in this short time, the technology has matured enough to have proven its worth and will, perhaps, continue to improve in the future. Systems developed thus far seem to adhere to specific architectures and characteristics imposed by the stringent surgical environment.

3. Common Components of Surgical Robotic Systems

Perhaps The most important and specific component of the surgical robot is the manipulator. Surgical manipulators are electro-mechanical arms equipped with sensors and actuators responsible for holding and precisely moving the surgical instrument under computer control. The most common kinematic architecture of surgical manipulators has thus far been the Remote Center of Motion (RCM), which is a specific characteristic of surgical robots as opposed to industrial types.

The RCM is a mechanism used by the surgical manipulator to enable and facilitate the pivoting motion of instruments about a fixed point in space, normally located on the instrument itself. This mechanism enables minimally invasive instruments to preserve a consistent entry point, or port, throughout the entire procedure. This technique was developed by observing the surgeon’s natural motion in manual laparoscopy. The RCM is a mechanism that accomplishes the same task. Following the insertion of the instrument, the RCM causes it to pivot about a fixed point in space--the point where it enters the body. Different robots use more or less sophisticated means of implementing the RCM, but there are very few surgical systems not using this principle today. In fact, all commercially available surgical robots are RCM-based robots.

Another important general component of medical robotic systems is the image acquisition device. This may generally be any medical imaging device (video, infrared, ultrasound, x-ray, or MRI), although imager compatibility issues exist, especially for the class of MRI scanners. Minimally invasive surgery utilizes intraoperative video and/or infrared cameras to provide the surgeon with a view of the surgical area. Since laparoscopy is highly dependent on the quality of the image the surgeon sees, there has been considerable recent progress in optimizing laparoscopic imaging. Presently in use, stereo endoscopes allow for 3D visualization of the surgical field [15]. This increases surgical performance by facilitating more precise dissection between delicate anatomical planes and razor-sharp precision when handling sutures and minute tissue layers [16, 17]. Unfortunately, many of the current technologies for 3D imaging are bulky and difficult to use. High definition (HD) imaging is now available, although not in widespread use. HD camera chips produce more than 2 million pixels of resolution (or approximately 4 times better than the best traditional camera chips). It is estimated that the current cost of a complete HD video system for the operating room ranges between one-quarter and one-half million USD [15]. Although cost presently prohibits many laparoscopic centers from using HD technology, as the technology matures and costs drop, it is only a matter of time before HD technology becomes standard operating room technology.

The computer is the third general component of the surgical robotic system. Surgical robots bring computers into the operating room in a new way, providing a link between the “data world” of medical images, sensors and databases, and the physical world of surgical actions. This combination makes it possible to plan and execute surgical interventions precisely and predictably by fusing real time and pre-surgical information about the patient. This information can then be used to improve surgical decision-making and real time control of surgical instruments. As robotic systems continue to incorporate real time control and sensing, interventions will become more consistent and accurate than freehand interventions.

Furthermore, the computer inherently has the ability to acquire and retain a great deal of information about each intervention. For example, how much force was applied? For how long? Where, exactly, was a suture placed? Many such questions have yet to be quantitatively understood. Currently, the analysis of such log data attracts a good deal of attention within the medical robotics research community. As research progresses, we expect that lessons will be learned and additional experience will be acquired by surgeons through the use of these new “smart” tools. This will, in turn, improve surgical quality and outcomes, in much the same way that similar uses of data have improved manufacturing quality and flight safety.

4. Image-Guided Robotic Systems:

The idea behind Image-Guided Robotic Systems is to allow the surgeon to "point and click" on a medical image of a location within an organ, approve his or her selection and cause a robot to place a tool (a needle for example) at the physical equivalent of the position selected on the medical image. The first example of such a system was the work of Potamianos et al. described previously.

The Johns Hopkins URobotics Laboratory [18] has developed several robotic components for image-guided percutaneous access. PAKY is an active and radiolucent needle driver [19]. Originally held by a passive arm, the needle in the needle driver was manually positioned under C-Arm guidance. It was then locked in place and the needle inserted automatically under the surgeon’s joystick control [20]. The next step was to automate the needle orientation procedure, which was accomplished with the addition of the RCM module [14]. The RCM supports and orients the PAKY driver while maintaining the fixed location of the needle tip. The combination of the two robotic systems enables the surgeon to automatically place the needle at a target specified on the computer screen by the urologist, based on the fluoroscopic images [21]. The PAKY-RCM offers an unquestionable improvement in needle placement accuracy and lowers procedure time while reducing radiation exposure to patient and urologist [22].

Clinically, the PAKY-RCM system was tested in local as well as in several transatlantic telesurgical cases [23]. The PAKY-RCM system was also used under CT guidance with the Laser-Based CT/MR Registration [24]. This method of registering the patient to the image makes use of the laser markers readily available on any CT scanner. Once registered in this manner, the organ of interest can be targeted precisely. The procedure was successfully used for biopsies and radio-frequency (RF) ablation of targets on the kidney and spine, as well as for nephrostomy tube placements [25].

The newest robotic system from the Johns Hopkins URobotics Laboratory is called Tracker (Figure 1). It is mounted on the CT table and enters the scanner along with the patient [26]. Percutaneous access is achieved in the confined space of the imager without interfering with imager functionality. Tracker has undergone final laboratory evaluations and is now under clinical trial [27, 28].

The imaging method that yields perhaps the best quality soft tissue images is the MRI. Unfortunately, this is also the most difficult imaging method in which to work for a traditional (metal) robot. The high magnetic fields of the MRI cause forces equal to 27 times gravity on ferromagnetic metal objects, as well as heating them and causing other undesirable effects. Despite these difficulties, there is strong motivation for building an MRI-compatible robot because of the imaging capabilities of this technology. While CT scans are becoming more accurate, even spiral CT cannot provide as much information as MRI for many pathologies and organ systems. Using a CT scan, it is often possible to see small, suspicious areas in the prostate, yet have extreme difficulty accurately targeting these areas with the biopsy needle by relying on printed images and simultaneous TRUS. It can certainly be frustrating to see a lesion without having the option to locate it outside the scanner. The ideal solution is to be able to biopsy it under the real time guidance of MRI images.

Figure 1: Tracker robot for CT guided interventions, URobotics, JHMI

There are several research groups currently examining this problem. One MRI-compatible system for non-invasive surgery has been developed by Hynynen et. al. [29]. Another MRI-compatible device, a needle insertion manipulator using ultrasonic actuation, has been built by Masamune et al. at the University of Tokyo [30] and tested on phantoms. Yet another system is currently under investigation at Brigham and Women's Hospital, Boston, MA. This is a robot with two long arms which extend into the imaging field by entering the space between a specially designed "double donut" MRI scanner [31]. The system can be used as an image-guided surgical assistant, integrating pre-operative planning and intra-operative MRI images. The Johns Hopkins University URobotics laboratory is also working on a multi-imager-compatible robot with MRI capability for precise prostate access that incorporates a new kind of harmonic and planetary motor [32]. While there is much current research toward building MR-compatible robots, there are no commercial, clinically applicable systems of this type at the present time.

Another interesting system is under investigation by an Italian group. It uses a different strategy to improve the link between medical images and reality. They have developed and evaluated an ultrasound-guided robot for use in transperineal biopsies [33, 34]. This system uses four real-time video cameras and integrates this information with data gathered from the TRUS to position the robot for sample collection. Although the system has demonstrated target accuracy of 1-2 mm, expense and set-up time presently hinder feasibility.

A system for prostate brachytherapy under TRUS guidance is under development in the JHU URobotics laboratory in collaboration with the CISST Engineering Research Center and Burdette Medical Systems, Inc. Recently, a first evaluation has been successfully completed on phantom models [35] (Figure 2) and a specifically designed robot, which will integrate with the Burdette brachytherapy stand and their dosimetry algorithms, is currently under development. This system will take advantage of advancements in ultrasound technology that enable the TRUS alone to be precise enough to hit targets accurately without the need for a cooperative, concurrent imaging modality.

Figure 2: System for ultrasound-guided robotic brachytherapy (JHU & Burdette Medical)

5. Surgeon-Driven Robotic Systems:

In contrast to image-guided robots, which automatically manipulate instruments under the prescription of the physician based on the digital image information, surgeon-driven systems continuously take the surgeon's input and, in real time, translate it to corresponding instrument manipulation. Surgeon-driven robots augment the manipulation capabilities of the physician in ways that passive, classic instruments cannot. They can decrease tremor, scale motion, aid in manipulation of tissues in confined spaces and have the potential to provide remote haptic (tactile and force) feedback. They thereby enable decreasingly invasive operations to be performed.

The first Surgeon-Driven surgical assistant to receive FDA clearance was the Automated Endoscopic System for Optimal Positioning (AESOP™), a robotic, laparoscopic camera holder from Computer Motion, Inc., Goleta, CA. The AESOP™ has six degrees of freedom (DOF), two of which are passive (meaning they are positioned by hand and do not have motors actuating them). AESOP™ is easily mounted on the OR table and can be conveniently stored away, mounted on a special cart. The function of AESOP™ is to hold and orient a laparoscopic camera under hand, foot or voice control [36]. The two passive joints prevent lateral forces on the abdominal wall during camera manipulation.

Perhaps the primary reason for AESOP™'s success is that it is simple to operate and, at the same time, reliable and safe. Additionally, the robot is easy to disconnect intraoperatively in the (highly unlikely) event that problems should arise. AESOP™ is routinely used at several institutions and in many surgical disciplines including a variety of laparoscopic urologic procedures [37-39]. The camera is significantly steadier under robot control and neither operative set-up nor breakdown time is increased with the use of a robotic assistant [40].

A Surgeon-Driven system to manipulate instruments designed for open surgery has been developed at the Stanford Research Institute (SRI), Menlo Park, CA. The surgeon operates the two-armed robot equipped with high-mobility grippers from a remote console. Bowersox and colleagues have used the system for in vivo porcine nephrectomies and repair of bladder and urethral injuries [41].

Perhaps the most successful surgeon-driven robot thus far is the daVinci™ system for laparoscopy (Intuitive Surgical, Inc., Mountain View, CA). The system was tested in early 2000 in Europe by cardiovascular surgeons performing laparoscopic cardiac bypass operations without using an extracorporeal cardiopulmonary bypass [42]. The daVinci™ system consists of a three-armed robot connected to a remote surgeon console (Figure 3). The surgeon operates the system while seated at the non-sterile console. The vision system is controlled using foot pedals and displays a 3D image of the surgical field similar to that seen in the open surgery case. The surgeon's movements are translated in real-time to movements of the pencil-sized instruments in the surgical field. These enter the patient through small ports (on the order of 5-10 mm, depending on the tool). Two of the robotic arms are used for manipulating the surgical instruments, while the third arm manages the laparoscope. The instruments (needle holders, scissors, dissectors, scalpel, etc.) have seven DOF including rotation, and are maneuvered by a robotic wrist.

Figure 3: AESOP arm (foreground - left) and daVinci system (background - left, and surgeon's console - right) in a laparoscopic prostatectomy case at JHMI

Using the daVinci™ system, one can bypass much of the long learning curve traditionally associated with minimally invasive surgery. This is because the device automatically orients tool motion with respect to the camera view. Move your hand up and the tool moves up in the image, regardless of whether this lies physically in the same direction. Thus, the difficult, inverted, counter-intuitive movements of conventional laparoscopy are eliminated and replaced by natural hand-eye coordination. Also possible is the re-orienting of the surgeon's hands to more comfortable positions. With traditional laparoscopic tools, it is sometimes necessary to work with arms uncomfortably contorted in order to reach an object with the tools at the proper orientation. Using daVinci™, the surgeon can move the tools to the proper location and orientation, press a button to hold them in place while he moves his controls to a comfortable position and then resume control of the tools. The daVinci™ system was cleared by the FDA in mid-2001 and is already in use at many centers throughout the USA in several surgical disciplines. Robot-assisted urologic surgery has already been successfully performed for partial/total and donor nephrectomies, pelvic lymphadenectomy, pyeloplasties, cryoablation procedures, diagnosis and treatment of cryptorchidism, as well as for radical prostatectomy and retroperiteoneal procedures [43-47].

A competitor system is the Zeus™ system from Computer Motion (the makers of AESOP™). Similar to daVinci™, Zeus™ consists of the combination of three robot arms and surgeon's control console. The system uses one AESOP for the laparoscope and the other two arms hold surgical instruments. Compared to daVinci™, Zeus™ appears safer and requires significantly less preoperative setup. On the other hand, until recently, Zeus™ had exhibited lower dexterity of the tools within the patient. However, the company seems to have recently addressed this with the MicroWrist™ line of end-effector tools. Zeus™ received FDA clearance as a general laparoscopic tool in September, 2002. The system has been experimentally used in a number of operations including urology cases [46, 48]. Most recently, Dr. Peter Schulam at UCLA has used the system for reconstructing the kidney’s draining system [49].

Although very precise, present robotic systems lack the capability of completely reproducing tactile sensation (known as haptics). Some systems, such as Zeus™, include partial force feedback [50], but realistic, general haptic feedback is still a research topic. While daVinci does have some haptic feedback capability, this is usually disabled when the robot is used because it does not provide a realistic feel. This is primarily because the forces are sensed from outside the patient, causing forces generated at the port to have a predominant effect, disturbing the sensation of forces experienced at the tip of the instrument. Haptics is an active research topic within the engineering community [51, 52]. A good deal of work has been done investigating new kinds of tactile sensors [53-57]. There are also theoretical questions as yet unanswered about how best to display haptic information and there are a number of technical obstacles to overcome in hardware development, signal processing and systems integration before general haptic feedback will be possible [56-58]**.**

6. Telemedicine, Telementoring, Telesurgery:

The real time data exchange of medical information between physicians in different locations is known as telemedicine. Telementoring describes the assistance of an experienced surgeon in a remote operation, while telesurgery implies his or her active involvement in the operation, manipulating instruments through the use of remotely controlled robots. The increasing accessibility of telecommunication systems, ranging from simple telephone lines to high-bandwidth fiber-optic and satellite transmissions [59], allows physicians to communicate with their peers over any terrestrial distance. Teleconferences, broadcast surgeries and consultations of specialists are common today along with the worldwide exchange of medical images and data through the Internet. Surgical teleconsulting has been demonstrated to improve medical decision making, patient outcomes and medical training [60]. Instead of being forced to travel long distances to other countries, specialists can now be available at any desired location for conferences or meetings while they sit at their office desks. Telemedicine has been successfully carried out over long distances between hospitals in the USA and Europe. Initial reports of telementoring and telesurgery were published as early as 1994 by Kavoussi et al. [39, 61] and followed by a variety of intercontinental operations [23, 41, 45, 47, 62-68].

In most cases, the surgeon remotely operated one or two robots, assisting the surgical team at the local hospital. The surgery begins with the local team setting up the operation: inserting the trocars and positioning the robots. Then, the remote surgeon controls only the laparoscope held by the robot to obtain a view of the surgical field. He/she also, in some cases, uses a telestrator to illustrate incision lines, anatomical structures or critical areas visually to the local team [69]. The lag times for transmission of data have all been reported to be less than 200 milliseconds, which is hardly noticed during the procedure [61, 69, 70].

By using an additional robot like the PAKY-RCM, the remote surgeon can actively retract organs or insert needles . The first transatlantic, assisted telerobotic surgery using two robots was successfully performed between Baltimore, MD, and Munich, Germany, in April, 2001 [71]. The remote surgeon controlled the laparoscope from his house via the AESOP™ robot, as well as a laparoscopic retractor with the PAKY-RCM robot. Active involvement in the operation was achieved by managing the gas inflation, telestration and electrocautery (Figure 4). For the transmission of the audio and video signal as well as robot control, a total of 512 kilobits per second (kbps) was needed, delivered by four ISDN lines at 128 kbps each. Although the remote expert was half a world away from the patient, his active involvement in the operation, along with the live visual and audio displays, gave the feeling of the expert's being in the operating room.

Figure 4: Remote controlled instrumentation and Munich operating room in telesurgery case

The most profound example of telesurgery thus far is known as "Operation Lindbergh." This surgery was carried out using the Zeus™ robotic system between New York, USA, (remote location) and Strasbourg, France, (patient location). The procedure was a complete laparoscopic cholecystectomy, and was performed in September, 2001. The surgery was carried out by Dr. M. Gagner (remote surgeon) under the local supervision of Professor J. Marescaux, and was a complete success [67]. The event achieved worldwide recognition [63, 64] in popular and scientific media.

One of the future goals of telesurgery is to deliver healthcare in medically underserved areas and thereby limit patient transportation [65]. Additionally, telesurgery has applications in armed conflicts where qualified medical care may not be readily accessible. This scenario was successfully investigated with telementoring via satellite connection between an aircraft carrier and a medical center in the USA [72]. In the long term, telesurgery could also be used in the long-lasting, manned space missions of the future.

Before these goals become a reality, however, several issues must be addressed. Telemedicine of any kind is dependent on continuous and high quality signal transmission [59]. Although local setup does not theoretically require a surgeon, experienced surgeons must be on hand at the patient's location, ready to take over the operation in case of system or transmission failure. Additionally, due to the necessary technical assistance in both locations, coordination of such efforts, especially across several time zones, has proved challenging.

Another source of difficulty is the fact that medical technology is currently advancing too rapidly for legislation to keep pace. Among the issues needing to be addressed are interstate and international licensure regulations, billing, informed consent and malpractice insurance. It may be necessary to institute committees to set international standards, rules, regulations and safety measurements for the protection of the patient. The stringent technical requirements and costs of telesurgery are currently satisfied only by specialized centers throughout the world. However, the field is expected to expand in the future through wider distribution of robotic systems, and as reliable low cost communication systems become more readily available.

7. Training devices for minimally invasive techniques:

As mentioned earlier, there is currently a worldwide demand for laparoscopic specialists in many fields of surgery. Since there is an insufficient number of qualified training programs available, surgeons currently attend training courses or observe procedures at specialized centers. While initial direct experiences with experts are very important, a constant exposure to the experience of laparoscopic manipulation is mandatory to keep and expand the acquired skills [63]. In a comparison of surgeons who attended a laparoscopic course, See et al. [73] found a three-fold increase in the complication rate for surgeons who did not continually perform minimally invasive procedures as compared to their course colleagues who did [73, 74]. It is therefore crucial not only to train qualified laparoscopic surgeons in certified programs, but also to ensure ongoing practice and mentoring.

Laparoscopy can be efficiently trained and tested using robotic devices, allowing instrumentation to be manipulated while various techniques and difficult situations can be simulated. Using these tools, tutoring by experienced minimally invasive surgeons as well as self- or computer-guided, hands-on training can be performed in a stress-free environment.

A 3-step laparoscopy training system is near completion in our URobotics laboratory [18]. The first of these devices allows the trainee to become accustomed to the inverted manipulation of laparoscopic tools under direct (3D) vision. Using this system, the trainee inserts instruments through ball-joint trocar ports and operates on phantom or animal specimens. The Step 2 trainer is a closed box with similar entry ports for training under 2D visualization. The Step 3 trainer, presently in the experimental stages, replaces the opaque box used in the Step 2 trainer with a high-fidelity synthetic torso (Figure 5) which follows the male anatomy of the Visual Human Project of the National Library of Medicine (NLM). This Step 3 trainer closely simulates true human laparoscopy and reduces the need for surgical training on animals. The torso allows for the *in situ* inclusion of abdominal animal organs, presents a disposable abdominal wall that can be pressurized and also includes respiratory simulation by connecting the torso to a respirator.

Figure 5: High-Fidelity synthetic torso for urologic laparoscopy training (URobotics, JHMI)

The ideal laparoscopy training method would be Virtual Reality (VR) based. In surgery, VR trainers provide the opportunity to learn through interacting with a simulated 3D environment. The VR student can perform many different scenarios and create diverse teaching modules [75]. VR training can provide performance feedback and, perhaps someday, provide certification standards for training urologists [76, 77].

A VR flexible ureteroscopy simulator (HT Medical, Inc., Rockville, MD) allows surgeons to practice navigating through, and evaluating, the urinary collection system. Perhaps the most advanced VR simulators in urology thus far have been created by Dr. Manyak's research group at George Washington University. The GWU team uses the Visible Human dataset for generating surface-based geometric data. Their systems are specialized VR trainers providing a realistic experience of the lower urinary tract in endoscopic procedures [78]. The group has developed and continues to expand a computer-based surgical simulator that incorporates a surgical tool interface with anatomic detail and haptic feedback.

The use of VR in training has demonstrated that more experienced laparoscopic surgeons perform surgical tasks with greater accuracy and efficiency than less experienced surgeons [79]. Improvements in collision-detection and graphics, among other things, are presently in testing. Clearly, the widespread distribution of realistic training devices has the potential to improve the skill of laparoscopic urologists worldwide.

8. Conclusion:

New tools, such as surgical robots, open diverse and promising possibilities for improving existing surgical techniques. They also have the potential to enable new procedures heretofore impossible without the aid of this technology. Among many other advantages, robots are often able to improve the dexterity and precision of minimally invasive surgery over manual procedures. Further, the robot provides a way of performing an essentially exact mapping between images given by sophisticated medical imaging equipment and the actual patient.

Several surgical robotic systems have been developed, tested and cleared by the FDA. Some of these have already demonstrated powerful clinical utility within urology. With continued technological improvements and the emphasis of both sides on strong partnerships between doctors and engineers, surgical robotics will continue to open new horizons in the practice of urology.

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Disclosure:
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References:

1. Stoianovici D, Cadeddu JA, Kavoussi LR. Urologic Application of Robotics. American Urological Association - 1999 AUA Update Series. Vol. XVIII, 1999:(Lesson 25) 194-200.
2. Caddedu JA, Stoianovici D, Kavoussi LR. Telepresence and Robotics: Urology in the 21st Century. Contemporary Urology 1997; 9:86-97.
3. Suryanarayanan S, Reddy NP, Gupta V. An intelligent system with EMG-based joint angle estimation for telemanipulation. Stud Health Technol Inform 1996; 29:546-52.
4. Mack MJ. Minimally invasive and robotic surgery. Jama 2001; 285:568-72.
5. Cadeddu JA, Stoianovici D, Kavoussi LR. Robotics in urologic surgery. Urology 1997; 49:501-7.
6. Buckingham RA, Buckingham RO. Robots in operating theatres. Bmj 1995; 311:1479-82.
7. Davies BL, Hibberd RD, Coptcoat MJ, Wickham JE. A surgeon robot prostatectomy--a laboratory evaluation. J Med Eng Technol 1989; 13:273-7.
8. Davies BL, Hibberd RD, Ng WS, Timoney AG, Wickham JE. The development of a surgeon robot for prostatectomies. Proc Inst Mech Eng [H] 1991; 205:35-8.
9. Potamianos P, Davies BL, Hibberd RD. Intra-operative imaging guidance for keyhole surgery: methodology and calibration, International Symposium on Medical Robotics and Computer Assisted Surgery, Pittsburgh, PA, 1994.

10. Potamianos P, Davies BL, Hibberd RD. Intra-operative registration for percutaneous surgery, International Symposium on Medical Robotics and Computer Assisted Surgery, Baltimore, MD, 1995.
11. Taylor RH, Funda J, Eldridge B, et al. A Telerobotic Assistant for Laparoscopic Surgery. IEEE Engineering in Medicine and Biology Magazine, 1995:279-287.
12. Taylor RH, Funda J, Grossman DD, Karidis JP, LaRose DA. Remote Center-of-Motion Robot for Surgery. 5,397,323, Mar. 14
13. Bzostek A, Schreiner S, Barnes A, al. e. An automated system for precise percutaneous access of the renal collecting system. In: CVRMed-MRCAS, ed. Lecture Notes in Computer Science: Springer-Verlag, 1997:1205-1299.
14. Stoianovici D, Whitcomb L, Anderson J, Taylor R, Kavoussi L. A Modular Surgical Robotic System for Image-Guided Percutaneous Procedures. In: Lecture Notes in Computer Science, Medical Image Computing and Computer-Assisted Interventions, Cambridge, Mass, October 11-13, 1998. Vol. 1496. Springer.
15. Kourambas J, Preminger GM. Advances in camera, video, and imaging technologies in laparoscopy. Urol Clin North Am 2001; 28:5-14.
16. Babayan R, K, Chiu A, W, Este-McDonald J. The comparison between 2-dimensional and 3-dimensional laparoscopic video systems in a pelvic trainer. J Endourol 1993:7: S195.
17. Chiu AW, Babayan RK. Retroperitoneal laparoscopic nephrectomy utilizing three-dimensional camera. Case report. J Endourol 1994; 8:139-41.
18. Stoianovici D. URobotics--Urology Robotics at Johns Hopkins. Comput Aided Surg 2001; 6:360-9.
19. Stoianovici D, Kavoussi L, R., Whitcomb L, L., et al. Friction transmission with axial loading and a radiolucent surgical needle driver. United States Patent 6,400,979, June 4, 2002
20. Stoianovici D, Cadeddu JA, Demaree RD, et al. An efficient needle injection technique and radiological guidance method for percutaneous procedures. In: Lecture Notes in Computer Science, Medical Robotics and Computer-Assisted Surgery, Grenoble, France, March, 1997. Vol. 1205. Springer-Verlag.
21. Patriciu A, Stoianovici D, Whitcomb L, et al. Motion-based robotic instrument targeting under C-Arm fluoroscopy. In: Lecture Notes in Computer Science, Medical Image Computing and Computer-Assisted Interventions, Pittsburgh, PA, October 11-14, 2000. Vol. 1935. Springer-Verlag.
22. Cadeddu JA, Stoianovici D, Chen RN, Moore RG, Kavoussi LR. Stereotactic mechanical percutaneous renal access. J Endourol 1998; 12:121-5.
23. Bauer J, Lee BR, Stoianovici D, et al. Remote percutaneous renal access using a new automated telesurgical robotic system. Telemed J E Health 2001; 7:341-6.
24. Patriciu A, Solomon SB, Kavoussi LR, Stoianovici D. Robotic Kidney and Spine Percutaneous Procedures Using a New Laser-Based CT Registration Method. In: Lecture Notes in Computer Science, Medical Image Computing and Computer-Assisted Interventions, Utrecht, Netherlands, October 14-17, 2001. Vol. 2208. Springer-Verlag.
25. Solomon S, Patriciu A, Masamune K, et al. CT Guided Robotic Needle Biopsy: A Precise Sampling Method Minimizing Radiation Exposure. Radiology 2001; In Press.
26. Stoianovici D, Cleary K, Patriciu A, et al. TRACKER: A Robotic System for Radiological Interventions. IEEE Transactions on Robotics and Automation 2002: To Appear.
27. Cleary K, Stoianovici D, Patriciu A, Mazilu D, Lindisch D, Watson V. Robotically assisted nerve and facet blocks: a cadaveric study. Acad Radiol 2002; 9:821-5.
28. Cleary K, Xu S, Fichtinger G, Lindisch D, Glossop N, Stoianovici D. CT-Directed Robotic Biopsy Testbed. IEEE Transactions on Robotics and Automation 2002; To Appear.

29. Hynynen K, Darkazanli A, Unger E, Schenck JF. MRI Guided Noninvasive Ultrasound Surgery. Med Phys 1992; 20:107-116.
30. Masamune K, Kobayashi E, Masutani Y, et al. Development of an MRI-compatible needle insertion manipulator for stereotactic neurosurgery. J Image Guid Surg 1995; 1:242-8.
31. Chinzei K, Miller K. Towards MRI guided surgical manipulator. Med Sci Monit 2001; 7:153-63.
32. Stoianovici D, Kavoussi LR. Planetary - Harmonic Motor. United States Provisional Patent 60/411,906, Filed 9/19/02
33. Rovetta A. Tests on reliability of a prostate biopsy telerobotic system. Stud Health Technol Inform 1999; 62:302-7.
34. Rovetta A. Computer assisted surgery with 3D robot models and visualisation of the telesurgical action. Stud Health Technol Inform 2000; 70:292-4.
35. Fichtinger G, L. DT, Patriciu A, et al. Robotically Assisted Prostate Biopsy And Therapy With Intra-Operative CT Guidance. Journal of Academic Radiology 2001; 9:60-74.
36. Mettler L, Ibrahim M, Jonat W. One year of experience working with the aid of a robotic assistant (the voice-controlled optic holder AESOP) in gynaecological endoscopic surgery. Hum Reprod 1998; 13:2748-50.
37. Partin AW, Adams JB, Moore RG, Kavoussi LR. Complete robot-assisted laparoscopic urologic surgery: a preliminary report. J Am Coll Surg 1995; 181:552-7.
38. Sackier JM, Wang Y. Robotically assisted laparoscopic surgery. From concept to development. Surg Endosc 1994; 8:63-6.
39. Kavoussi LR, Moore RG, Partin AW, Bender JS, Zenilman ME, Satava RM. Telerobotic assisted laparoscopic surgery: initial laboratory and clinical experience. Urology 1994; 44:15-9.
40. Kavoussi LR, Moore RG, Adams JB, Partin AW. Comparison of robotic versus human laparoscopic camera control. J Urol 1995; 154:2134-6.
41. Bowersox JC, Cornum RL. Remote operative urology using a surgical telemanipulator system: preliminary observations. Urology 1998; 52:17-22.
42. Chitwood WR, Jr., Nifong LW. Minimally invasive videoscopic mitral valve surgery: the current role of surgical robotics. J Card Surg 2000; 15:61-75.
43. Binder J, Jones J, Bentas W, et al. [In Process Citation]. Urologe A 2002; 41:144-9.
44. Hemal AK, Menon M. Laparoscopy, robot, telesurgery and urology: future perspective. J Postgrad Med 2002; 48:39-41.
45. Rassweiler J, Frede T, Seemann O, Stock C, Sentker L. Telesurgical laparoscopic radical prostatectomy. Initial experience. Eur Urol 2001; 40:75-83.
46. Breda G, Nakada SY, Rassweiler JJ. Future developments and perspectives in laparoscopy. Eur Urol 2001; 40:84-91.
47. Rassweiler J, Binder J, Frede T. Robotic and telesurgery: will they change our future? Curr Opin Urol 2001; 11:309-20.
48. Schuessler WW, Schulam PG, Clayman RV, Kavoussi LR. Laparoscopic Radical Prostatectomy: initial short-term experience. Urology 1997; 50:854-57.
49. UCLA. Robots In Surgery: No Longer Science Fiction. Clark Urological Center Newsletter. Vol. 14, 2002:1-2.
50. Reichenspurner H, Damiano RJ, Mack M, et al. Use of the voice-controlled and computer-assisted surgical system ZEUS for endoscopic coronary artery bypass grafting. J Thorac Cardiovasc Surg 1999; 118:6-11.
51. Gerovichev O, Marayong P, Okamura AM. The Effect of Visual and Haptic Feedback on Manual and Teleoperated Needle Insertion, Medical Image Computing and Computer Assisted Intervention -- MICCAI 2002, Lecture Notes in Computer Science, 2002, 2002. Vol. 2488.

52. Kitagawa M, Bethea BT, L GV, Baumgartner WA, Okamura AM. Analysis of Suture Manipulation Forces for Teleoperation with Force Feedback, Medical Image Computing and Computer Assisted Intervention (MICCAI) -- Lecture Notes in Computer Science, 2002, 2002. Vol. 2488.
53. Wellman PS, Dalton EP, Krag D, Kern KA, Howe RD. Tactile imaging of breast masses: first clinical report. Arch Surg 2001; 136:204-8.
54. Pawluk DT, Howe RD. Dynamic contact of the human fingerpad against a flat surface. J Biomech Eng 1999; 121:605-11.
55. Pawluk DT, Howe RD. Dynamic lumped element response of the human fingerpad. J Biomech Eng 1999; 121:178-83.
56. Howe RD, Peine WJ, Kontarinis DA, Son JS. Remote Palpation Technology for Surgical Applications. IEEE Engineering in Medicine and Biology Magazine. Vol. 14, 1995:318-323.
57. Howe RD. Tactile sensing and control of robotic manipulation. Journal of Advanced Robotics 1994; 8:245-261.
58. Stoianovici D. Robotic surgery. World J Urol 2000; 18:289-95.
59. Broderick TJ, Harnett BM, Merriam NR, Kapoor V, Doarn CR, Merrell RC. Impact of varying transmission bandwidth on image quality. Telemed J E Health 2001; 7:47-53.
60. Demartines N, Mutter D, Vix M, et al. Assessment of telemedicine in surgical education and patient care. Ann Surg 2000; 231:282-91.
61. Lee BR, Caddedu JA, Janetschek G, et al. International surgical telementoring: our initial experience. Stud Health Technol Inform 1998; 50:41-7.
62. Ballantyne GH. Robotic surgery, telerobotic surgery, telepresence, and telementoring. Surg Endosc 2002.
63. Clayman RV. Transatlantic robot-assisted telesurgery. J Urol 2002; 168:873-4.
64. Larkin M. Transatlantic, robot-assisted telesurgery deemed a success. Lancet 2001; 358:1074.
65. Link RE, Schulam PG, Kavoussi LR. Telesurgery. Remote monitoring and assistance during laparoscopy. Urol Clin North Am 2001; 28:177-88.
66. Malassagne B, Mutter D, Leroy J, Smith M, Soler L, Marescaux J. Teleeducation in surgery: European Institute for Telesurgery experience. World J Surg 2001; 25:1490-4.
67. Marescaux J, Leroy J, Gagner M, et al. Transatlantic robot-assisted telesurgery. Nature 2001; 413:379-80.
68. Frimberger D, Kavoussi LR, Stoianovici D, et al. Telerobotic Surgery zwischen Baltimore und München. Urologe A 2002; In Press.
69. Micali S, Virgili G, Vannozzi E, et al. Feasibility of telementoring between Baltimore (USA) and Rome (Italy): the first five cases. J Endourol 2000; 14:493-6.
70. Fabrizio MD, Lee BR, Chan DY, et al. Effect of time delay on surgical performance during telesurgical manipulation. J Endourol 2000; 14:133-8.
71. Frimberger D, Kavoussi LR, Stoianovici D, et al. Telerobotische Chirurgie zwischen Baltimore und München. Der Urologe [A] 2002; 41:489-492.
72. Cubano M, Poulose BK, Talamini MA, et al. Long distance telementoring. A novel tool for laparoscopy aboard the USS Abraham Lincoln. Surg Endosc 1999; 13:673-8.
73. See WA, Cooper CS, Fisher RJ. Predictors of laparoscopic complications after formal training in laparoscopic surgery. Jama 1993; 270:2689-92.
74. Colegrove PM, Winfield HN, Donovan JF, Jr., See WA. Laparoscopic practice patterns among North American urologists 5 years after formal training. J Urol 1999; 161:881-6.
75. Satava RM, Jones SB. Preparing surgeons for the 21st century. Implications of advanced technologies. Surg Clin North Am 2000; 80:1353-65.
76. Arnold P, Farrell MJ. Can virtual reality be used to measure and train surgical skills? Ergonomics 2002; 45:362-79.

77. Laguna MP, Hatzinger M, Rassweiler J. Simulators and endourological training. Curr Opin Urol 2002; 12:209-15.
78. Manyak MJ, Santangelo K, Hahn J, et al. Virtual reality surgical simulation for lower urinary tract endoscopy and procedures. J Endourol 2002; 16:185-90.
79. Taffinder N, Sutton C, Fishwick RJ, McManus IC, Darzi A. Validation of virtual reality to teach and assess psychomotor skills in laparoscopic surgery: results from randomised controlled studies using the MIST VR laparoscopic simulator. Stud Health Technol Inform 1998; 50:124-30.