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Robotic surgery

Abstract The industrial revolution demonstrated the capability of robotic systems to facilitate and improve manufacturing. As a result, robotics extended to various other domains, including the delivery of health care. Hence, robots have been developed to assist hospital staff, to facilitate laboratory analyses, to augment patient rehabilitation, and even to advance surgical performance. As robotics lead usefulness and gain wider acceptance among the surgical community, the urologist should become familiar with this new interdisciplinary field and its "URobotics" subset: robotics applied to urology. This article reviews the current applications and experience, issues and debates in surgical robotics, and highlights future directions in the field.

During the course of the past century, man has developed numerous automated tools to increase productivity, quality, and product performance. As the need for production versatility emerged, man created programmable tools which could easily adapt to new operations. These systems, usually termed as robots, are mechanical systems controlled by microprocessors and equipped with sensors and motors. Computer algorithms utilize the environmental information and operator input provided by the sensors, to determine appropriate motor commands for the mechanical system to perform the desired task, which can be easily modified by software. The task may be preprogrammed, as for automobile production lines, or defined on-line by the operator in more complex tasks requiring immediate human decision.

The economic advantages, increased precision and improved quality demonstrated by industrial robots stimulated the application of robots for health care delivery. There are four main categories of medical applications in which robots have been pursued: supportive, laboratory, rehabilitative, and surgical. Supportive and laboratory robots have been developed as patient, hospital staff, and laboratory assistants. For example, Help-Mate [16] (Transitions Research Corporation, Milford, CT) is a commercially available robot which serves as a courier inside hospitals, delivering patient meals, medications, and X-rays. Robotic applications have been intensely investigated to assist people with manipulative disabilities. These would enable the person to control artificial limbs and help locomotion [30, 48].

The utilization of robots in surgery was pioneered in the 1980s in the fields of neurosurgery and orthopedic surgery [2, 4, 6, 43]. Intracranial neurosurgical procedures were a major focus of the first robotic systems, in part because a high degree of precision was required for localization and manipulation within the brain, and also because cranial anatomy provided relatively fixed landmarks. Three broad types of devices have been developed to improve spatial accuracy and surgical precision [18, 25]: neuronavigators, stereotactic localizers, and robotic assistants. In orthopedic surgery, robots have been developed to cut or ream bone. The RoboDoc system (Integrated Surgical Systems, Inc., Sacramento, CA) prepares the proximal femur to accept an uncemented total hip prosthesis [34]. The cavity it creates is 10 times more accurate than can be achieved by manual reaming.

Medical robotics has since expanded to other surgical applications, including urology. Robotic devices to assist urologists with transurethral resection of the prostate, percutaneous renal access, laparoscopy, and brachy-

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therapy are currently in developing stages or already in clinical use. Many prototype robotic systems have been developed and at present several systems are available commercially. Despite the large variety of surgical fields and applications, these systems present several common characteristics.

The most common configuration encountered in surgical applications is the manipulator, a structure presenting an arm-like configuration. Due to the complexity of most surgical tasks, the applicability of preprogrammed robots in surgery is limited [3, 5]. Most of the surgical robots today, take advantage of the surgeon's perception and judgment through the use of an on-line input device through which the surgeon dictates robotic movement during the procedure. There are now particularly effective and relatively new types of on-line controlled systems which are called "synergetic" [45, 47]. In these systems the surgeon and the robot impart motion by commonly holding the instrument. The surgeon remains in control of the procedure while the device provides steady-hand manipulation of the instrument. Finally, an important class of surgical robots utilizes imaging technology to position, guide (track) and monitor the robot as it performs the task under X-ray fluoroscopy, computed tomography (CT), ultrasound, or magnetic resonance (MR) imaging. This article presents a brief review of several robotic systems, current research, applications, and future goals in surgical robotics.

Present state of surgical robotics

The development of surgical robots is highly demanding compared to other fields, due to the enhanced safety, sterilization, compactness, operating room requirements, compatibility with medical imaging equipment, and the special ergonomics required. Testing and evaluation of the surgical robots is a laborious process, undergoing several non-clinical stages and endorsements before clinical assessment. Moreover, robotics for soft tissue operation, such as the urologic systems, should adapt to the deformability and mobility of the operated organ. Although these difficulties have delayed the evolvement of surgical robotics until the late 1980s, recent innovative research has allowed the development of several purpose-designed systems. This section outlines several surgical systems, some of which are presently used in the operating room, while some other are still under development.

The first "urobot" was introduced in 1989 by a group at the Imperial College in London, for performing transurethral resection of the prostate (TURP) [14, 15]. The relatively fixed positioning of the prostate and the fact that TURP requires repetitive movements in a specific geometric pattern, made robots good candidates for performing this operation. The development involved several design stages, trials, and refinements. When activated, the robot automatically generated a sequence of overlapping cuts in successive larger rings, starting at the hypothetical bladder neck. Clinical trials in five patients demonstrated that the entire resection could be performed rapidly with hemostasis achieved manually after the final cut. Unfortunately, trials identified the need for modifications including an alternative to transrectal ultrasound (TRUS) for prostate imaging as it was found to be insufficiently accurate [31, 32]. Although not absolutely prevailing, this system was the first recorded robotic surgery in humans unaided by the surgeon, and the first urobot.

The group at the Imperial College also investigated a robotic system to assist the urologist with intraoperative percutaneous renal access [36]. They employed a passive, encoded, 5 degree of freedom (dof) manipulator, 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 [35]. Initial experiments evaluating system performance demonstrated a targeting accuracy of less than 1.5 mm though in vitro experiments. In vivo experiments have not been performed to date.

Similarly, the medical robotic research group at the Johns Hopkins University developed an experimental system to perform percutaneous renal access [3]. This system primarily differs from the Imperial College system in that it employs an active robot (LARS, developed in collaboration with IBM) and it employs a bi-planar fluoroscopy imager. The surgeon chooses the target calyx in the two normal images, after which the robot positions the needle and inserts it to the desired location. In vitro and ex vivo porcine experiments demonstrated an impressive accuracy of less than 1.0 mm. Live porcine percutaneous renal access experiments revealed a success rate of placing a needle on the first attempt of only 50% [7]. Problems encountered were related to kidney displacement by needle insertion, needle deflection, and rib interference, although this system demonstrated the feasibility of performing fully automated robotic needle placement in soft tissue.

After extensive observations of surgeons performing needle insertion, our urobotics research group at John Hopkins (http://urology.jhu.edu/research/urobotics/) developed a robotic system, PAKY-RCM that mimics and improves upon the surgeon's standard technique. The system is based on an active and radiolucent needle driver, PAKY (percutaneous access of the kidne*y*) [41]. PAKY employs a novel kinematic principle, the friction transmission with axial loading [42], which was uniquely suited for a miniaturized radiolucent construction providing motorized needle actuation. PAKY is mounted into the remote center of motion (RCM) robot, which has an extremely low profile, making it compatible with portable X-ray fluoroscopy units (C-Arm) and CT scanners (Fig. 1).

The system is at present being used for percutaneous renal access at John Hopkins, offering an unquestionable improvement in needle placement accuracy and

Fig. 1 The PAKY – RCM robot for image guided percutaneous access

procedure time while reducing the radiation exposure to patient and urologist [8]. At the present time, PAKY is under continued evaluation and new C-Arm based image guidance algorithms are under development.

Another image-guided robot that has been evaluated clinically is a robot developed at the Politecnico of Milan, Italy, which is intended to perform a transperineal prostate biopsy [38, 39]. Using transrectal ultrasound, this system has demonstrated an accuracy of 1–2 mm in positioning the needle. Four video cameras recorded the position and configuration of the patient's body and integrated this with a TRUS image of the prostate to allow positioning of the robot and needle. The surgeon chooses the biopsy site from the TRUS images and the robot obtains the sample. Broad clinical use is unlikely in the near future due to the expense and set-up time. Nevertheless, this biopsy robot demonstrated the advantages of a robotic system including increased accuracy, more reliability as the robot maintained its position without any drift, needed less time for the procedure, and decreased patient discomfort.

An important and most recent class of image-guided systems concerns the development of basic or more advanced magnetic resonance (MR) compatible instrumentation, such as robotic assistants [10, 23, 29]. A MR-guided system for non-invasive surgery with high-intensity focused ultrasound (HIFU) has been developed by Hynynen et al. [23]. The system was actuated by ultrasonic (piezoelectric) motors [12]. A MR compatible needle insertion manipulator, also using ultrasonic actuation, was built by Masamune et al. at the Medical Precision Engineering laboratory of the University of Tokyo [29]. The system was designed for neurosurgery applications and tested on phantoms. A new system is at present under development as a collaboration between the Mechanical Engineering Laboratory, AIST-MITI, Japan and the Department of Radiology at the Brigham and Women's Hospital, Boston, MA. The latest version comprises a 5-dof manipulator and a "double donut" open MR scanner [10]. The robot is located between the vertical donuts, above the surgeon's head, and presents two 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 pre-operative planning and intra-operative MRI. It is expected that the system will shortly undergo laboratory testing.

Several devices have been developed for laparoscopy. They are manipulator arms helping the surgeon manipulate and position the laparoscope or advanced laparoscopic instruments under computer control [40, 44].

Perhaps the most successful commercial surgical robot to date has been the automated endoscopic system for optimal positioning (AESOP), which is a robotic laproscopic camera holder from Computer Motion, Inc., Goleta, CA (http://www.computermotion.com/) that has been used in many clinical areas, including urological laparoscopic surgery. AESOP was the first surgical robot to receive the approval of the Federal Drug Administration (FDA) and is now used clinically at several institutions. At Johns Hopkins, there has been considerable success in using this robot for a variety of laparoscopic urologic procedures [26, 27, 33]. In their studies, Kavoussi et al. [27] found that neither operative set-up nor breakdown time was increased with the use of a robotic assistant. In fact, robotic surgical assistants may be more economical than human assistants for laparoscopic surgery [33] and laparoscopic camera positioning was significantly steadier with less inadvertent movements when under robot control [27]. Partin et al. [33] have also reported their experience of using two robots (laparoscope and retraction) to perform one surgeon laparoscopy with no human assistance (Fig. 2).

AESOP was also used to assist in a variety of laparoscopic urologic procedures, including nephrectomy, pyeloplasty, retroperitoneal and pelvic lymph node dissections, and bladder neck suspension [40].

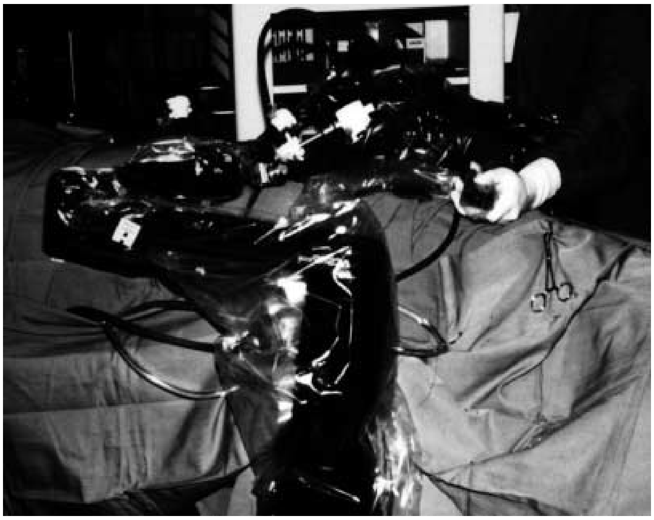

Fig. 2 Two AESOP robots performing one surgeon laparoscopy with no human assistance at the Johns Hopkins Medical Institutions

Advanced laparoscopic instruments have also been developed for increasing maneuvrability and dexterity, improving force feedback, and providing the sense of touch in laparoscopic procedures. A three-finger, wrist articulated, 7-dof miniature laparoscopic hand was developed by DAUM GmbH, Germany to increase "down-the-hole" dexterity. Two versions of this device have been developed. (Fig. 3): One is cable operated from a special glove-like device worn by the surgeon; the other uses the same miniature hand, but it is actively driven and controlled by a data glove in a master-slave architecture. The former case allows for remote operation of the mini-hand. The system has not yet been clinically tested. In vitro force feedback and dexterity experiments performed by our urobotics group characterized the first-generation EndoHand in comparison to current laparoscopic instruments. Although it falls short in both dexterity and tactile feedback, significant promise is shown in its ability to perform sophisticated manipulation of objects, and to work at a larger range of angles to the target tissue [24].

Regarding remote palpation technology, significant results have been obtained by the medical robotics group at Harvard University. One of a surgeon's most important tools is a highly developed sense of touch. New surgical techniques, however, separate the surgeon's hands from the surgical site (laparoscopy, robotic manipulation). To compensate for this deficiency, the research group at Harvard developed a variety of tactile sensors that can be mounted in a probe or surgical instrument [19–22]. They have also developed tactile display devices, which recreate the tactile stimulus directly onto the surgeon's fingertip (Fig. 4). Results of preliminary in-vitro and animal experiments, demonstrated that tactile sensing and display can convey important small-scale shape information from an inaccessible location to the surgeon's finger tips [19, 20]. Important questions remain to be addressed in hardware development, signal processing, and systems integration areas [9, 21, 22].

A remotely operated system for open surgical procedures funded by the DARPA (Defense Advanced Projects Agency) has been developed at the Stanford Research Institute (SRI), Menlo Park, CA. This system includes 3D video and audio communications, and two teleoperated 7-dof manipulators (6-dof arm + 1-dof gripper). The system is operated from a bilateral haptic interface with force feedback, which has identical architecture with the manipulators (Fig. 5). The system has been used successfully to allow a remote surgeon to perform open surgery with only a surgical assistant in the operating room. Cornum and colleagues have reported on their experience with the system for in vivo porcine nephrectomy and repair of bladder and urethral injuries [11].

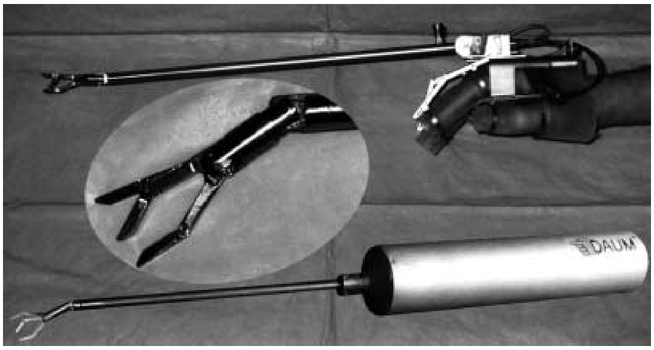

Fig. 3 The DAUM EndoHands: Local and remote

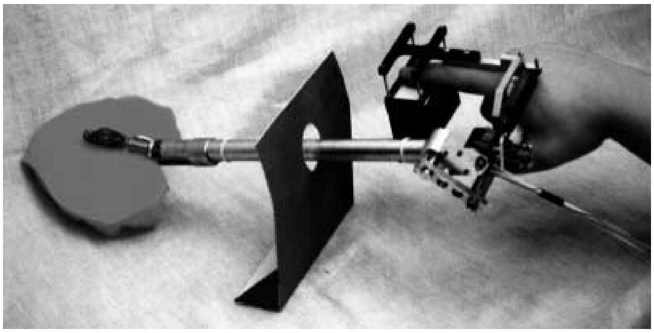

Fig. 4 Laparoscopic instrument for remote palpation developed at Harvard University

A recent generation of the SRI system has been developed for laparoscopy by Intuitive Surgical, Inc., Mountain View, CA (http://www.intusurg.com/). This system, named "da Vinci", has two primary components: the control console operated by the surgeon and the surgical arm unit, which holds and manipulates detachable surgical instruments. These pencil-sized instruments are equipped with a wrist, which provides additional dexterity. The system operates through 1 cm ports. Three surgical arms are maneuvered into place and inserted into the patient's body. The first arm holds the laparoscope while the other two arms may accommodate a variety of wrested instruments, such as needle driver, scissors, dissectors, scalpel, etc [17]. In early January 2000, Intuitive Surgical Inc. announced that by

Fig. 5 The SRI teleoperation system

using the da Vinci system, several cardiac centers in Europe have successfully perform totally endoscopic coronary artery bypass (TECAB) procedures on a beating heart. Figure 6 presents the da Vinci system in the operating room in Dresden, Germany.

This was the first time that cardiac bypass surgery was performed solely through less than 1-cm incisions without cardiopulmonary bypass (CPB). Just 2 months later the da Vinci system completed a mitral valve repair solely through four ports at the Deutsches Herzzentrum Cardiac Clinic in Munich, Germany. It is expected that in the near future this robotic system will extend its range of application to other surgical domains, be approved by the FDA, and investigated in the United States.

A competitive system, Zeus, was also designed for laparoscopic surgery by Computer Motion, Inc., Goleta, CA. It consists of three modified AESOP robots: one for the laparoscope and two for the instruments, and a purpose-built bilateral haptic interface (Fig. 7). A surgical assistant positions the robots and laparoscopic ports locally. The surgeon operates the system from the remotely located haptic interface, which handles in a similar way to the usual laparoscopic instruments. As the surgeon moves the haptic handles, the robotic manipulators in the operating room move in a similar fashion. Concurrently, force-feedback is returned to the surgeon on the gripper [37]. The system has not yet received FDA approval, being labeled as an investigation device. Compared to da Vinci, the Zeus appears safer and requires significantly lower preoperative set-up. On the other hand, Zeus exhibits lower maneuvrability and provides force feedback only on the grippers, whereas da Vinci has complete feedback on all axes. This is mainly due to the fact that Zeus is based on the AESOPS's, which have not been designed for master-slave operations, whereas da Vinci is a purpose-designed system. In addition, da Vinci's instruments present an extra "wrist", offering improved flexibility.

Fig. 6 The da Vinci Surgical System in the Dresden operating room

Fig. 7 Force-feedback experiments with Zeus at the Johns Hopkins Medical Institutions

Other commercial robotic systems include the ROBODOC System for hip replacement surgery [1] and the NeuroMate robotic arm for stereotactic brain surgery; both are from Integrated Surgical Systems (http://www.robodoc.com/).

Many experimental surgical systems are under development in academic institutions around the world. At the Carnegie Mellon University and Shadyside Hospital in Pittsburgh, clinical focus is on orthopedic applications [13]. Representative groups in Europe include the TIMC-IMAG group in Grenoble, France, with a recent project on robotic pericardial punctures [46, 47], and the Charite Hospital in Berlin, Germany, where one focus area is maxiofacial applications [28].

Future directions

Robotic applications open wide possibilities of improving upon current surgical techniques as well as allowing the development of new procedures, which could not be performed without the aid of this new class of surgical tools. Among many other advantages, these new instruments potentially improve the precision of manipulation as compared to manual procedures, and provide improved mapping between the patient and his volumetric image as given by sophisticated imaging equipment. This requires the development of miniature, extremely high-dexterity robots that are able to operate inside the image scanners, such as "open" as well as conventional "closed bore" CT and MR imagers.

The development of MR compatible robotic systems is a very challenging engineering task. MR scanners use magnetic fields of very high density, on the order of one tesla. Ferromagnetic materials, which are normally used for robot construction, undergo very high intensity forces when exposed to such fields. Concurrently, MR fields present variable components, thus inducing electricity in conductive elements, creating electrical interference, and overheating. In addition, the electromagnetic motors commonly used for robotic actuation would also interfere with the MR field. Novel engineering principles and methods should be developed to overcome these problems. This task demands a quantum leap in the current technology of mechatronic devices and clearly leads medical robotics into the next millennium.

Conclusion

A few surgical robotic systems have been developed to date and just a fraction of these demonstrated clinical utility to date. One should thus conclude that surgical robotics is still in its infancy. Several pioneering systems, however, have incontestably revealed the feasibility and utility of this technology. Considering the difficulty of implementing robotics into this highly demanding field, we should admit that significant progress has already been accomplished. With continued improvements in hardware and software, the application of surgical robotics will only expand. Physician acceptance of these systems will ultimately depend on their ability to advance surgical performance, improve patient safety, and reduce cost. Surgical robotics has the potential to open new horizons for the surgical practice.

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