1.1 Introduction

In the present era of telecommunications and computer technology, the way we live and work in both our professional and private environment have radically changed. Within this frame, the concept of automation and robotics has been extensively used in several fields of industry or hostile working environments. It has also recently been extended to medicine including assistance in complex surgical procedures.

In this chapter, we recall the marked achievements of the past few decades which have led to gradual implementation of robotics in medicine and especially in urologic surgery.

1.2 Background

The word robot, taken from the Czech word “robota,” meaning forced work, was used the first time in 1920 by the Czech writer Karel Čapek in his science fiction play “Rossum’s Universal Robots.” In the story, an inventor created and sold robots as a cheap labor force to the world; however, once the robots became anthropomorphic and highly intelligent, having feelings and able to make decisions, they realized their physical and mental superiority. They declared war on all humans and destroyed the entire human race.

The very first time a robot was used to assist a surgical intervention was in 1985. Kwoh [1] et al. in the Memorial Hospital of Los Angeles brought the industrial Unimation PUMA 200 robot into the operative room to hold a laser for neurosurgical interventions. Neurosurgery was a favorable candidate for testing robotic devices because the skull offers constant spatial landmarks. Stereotactic frames were developed for the purposes of biopsy and cranial stimulation.

Surgical robots fit into three categories: active; semi-active; and the so-called master–slave systems. The active system consists of a robot performing tasks autonomously under the supervision of the surgeon. Semiactive systems have an autonomic-and a surgeon-driven component. Master–slave systems allow the surgeon to directly telemanipulate the robot from a more or less remotely placed command center. In this situation, the surgeon’s movements are translated into robotic motion.

In urology, robots have been tested in two areas: endourology and laparoscopic surgery.
1.3 Endourology

1.3.1 Transurethral Prostate Resection

The earliest application of robotics to urological surgery began in 1989 with the group of the Mechanical Engineering Department at Imperial College in London. This group illustrated the ability of robots to perform precise, repetitive, and controlled tasks during transurethral resection of the prostate. They manufactured a prototype named PROBOT [2–4]. This is an autonomous robot, i.e., a system that executes surgical tasks following a preoperatively established plan. Firstly, the surgeon measures the distance between the bladder neck and verumontanum. Then, the prostate is scanned with an ultrasound probe passed into the resectoscope, allowing to build up a three-dimensional image of the prostate. Next, using this image, the surgeon designs on the computer console the cavity to be cut. The resection itself consists of cutting out a series of cones with the base of the cone at the bladder neck and the summit directed towards the verumontanum. PROBOT has been tested both in the laboratory and later on human subjects and has proved itself capable of performing prostate resection.

1.4 Ablatherm

A similar autonomous concept is used for the high-intensity focused ultrasound (HIFU) treatment of prostate cancer. The ABLATHERM device was created in 1993 at the Department of Urology and Transplantation, Edouard Herriot Hospital, Lyon, France, by Albert Gelet [5].

The device consists of a treatment and a control module. The patient is positioned on the treatment module. An ultrasound probe including the HIFU generator and the scanning equipment is attached to the treatment module via a mobile support; the latter executes robotic movements transmitted to the probe allowing delivering extremely precisely HIFU energy to preplanned areas of the prostate.

The control module enables the surgeon to first create the three-dimensional model of the prostate then plan and monitor the treatment via a computerized system which guides the robotic endorectal probe. The device is presently mass produced and validated for the treatment of prostate cancer in specific indications. By June 2005, the device was implanted to 76 sites worldwide and more than 7700 patients have been treated.

1.5 Prostate Biopsy

Based on the fixed position of the prostate within the pelvis, an Italian group developed a system which helps targeting transperineal prostate biopsies in 1995 [6, 7]. The SR 8438 Sankyo Scara robot allows accurate positioning based on the integration of ultrasound monitoring and the position and configuration of the patient’s body recorded by four video cameras. This experience was the first telerobotic procedure in urology.
1.6 Percutaneous Renal Access

Percutaneous access creation during nephrolithotomy or other nephroscopic procedures is challenging and requires substantial skill and experience. Inaccurate placement of the needle may be at the origin of severe complications by injuring the kidney and adjacent organs; therefore, in many urology departments, these tasks are relinquished to interventional radiologists.

A robotic system to assist the urologist with intraoperative percutaneous renal access was developed at the Johns Hopkins University. In the first prototype, the surgeon selected the target calyx on a biplanar fluoroscopy screen and the LARS robot inserted the needle into the desired location [8]. In a preliminary series of 12 patients, successful access on the first attempt was observed in 50% of cases. Needle or tissue deflection accounted for each failure.

A further development of this tool led to the PAKY (Percutaneous Access to the Kidney) device, which consists of a passive mechanical arm mounted on the operating table and a radiolucent sterilizable needle driver that uses an active translational mechanism for needle advancement [9]. The system utilizes real-time fluoroscopic images provided by a C-arm to align and monitor active needle placement. A second component was more recently added to the system: the remote center of motion (RCM) device consists of an active robotic arm attached to PAKY that allows the tip of the needle to pivot about the fulcrum point on the skin [10]. This allows the urologist to correctly align the needle along a selected trajectory path under remote fluoroscopic control at the console. This minimizes radiation exposure to the surgeon’s hand.

The success rate with this latest version of the device is 87% [10]. These preliminary results provide the foundations for the development of entirely automated robotically assisted percutaneous renal access.

1.7 Laparoscopic Surgery

The more popular platform for the application of robots in urology is laparoscopy. Since the early 1990s, laparoscopic surgery has aroused much interest in the field of urology and has become an integral part of daily practice in many specialized centers; however, the learning curve of laparoscopy is steep and for many established urologists in practice, fellowship training is unrealizable. The tremendous motivation to develop surgical robots stems from the desire to overcome the limitations of laparoscopic technology and to exploit the benefits of minimally invasive surgery.

1.7.1 Robotic Camera Holders

The voice commanded robotic manipulator AESOP (Automated Endoscopic System for Optimal Positioning) was conceived to control the laparoscope in response to the surgeon’s instructions. This robotic camera holder eliminates the need for an additional member of the surgical team, reduces instrument collisions, and offers a steadier endoscopic view. This was the first surgical robot that got U.S. Food and Drug
Administration (FDA) approval for clinical use in the U.S. in 1994. Since its introduction, AESOP has assisted in more than 45,000 procedures worldwide.

Solo-surgical laparoscopic radical prostatectomy was shown to be feasible and reproducible by Antiphon et al. in 2003, and the procedure is routinely used in some centers [11].

1.7.2 Master–Slave Systems

Undoubtedly, the biggest conquest of robotics in urology and especially in the field of laparoscopy was achieved after the birth of master–slave systems. The development of such systems was the result of several decades of experimental research.

Telepresence surgery was originally developed to be used when interaction of the surgeon and patient is unfeasible or unsafe. Experiments were done with the view of performing open trauma surgery in the battlefield with the surgeon controlling the manipulators from a safe, distant location. Both the Pentagon and the North American Space Association (NASA) evaluated the potential for remote surgery.

A functional master–slave manipulator for surgery was constructed by Jensen and Hill (SRI International, Menlo Park, Calif.) [12]. The SRI telemanipulator had only four degrees of freedom in its first versions. It was intended to be used mainly for remote surgery through telecommunication links, with particular emphasis on hostile environments such as military applications [13]. The first applications of the SRI system to open surgery were described by Bowersox et al. [14] in 1996, who used it for vascular surgery in pigs. He described dissection of the common femoral artery and closure of a 3-cm arteriotomy with a running suture through the master–slave manipulator in nine experimental cases. With this study, Bowersox et al. were able to demonstrate the feasibility of delicate surgical manipulations, such as vascular suturing techniques, via a master–slave manipulator system; however, the SRI system, in the configuration used by Bowersox et al., does not solve the problem of limited instrument mobility since it provides only four degrees of freedom of motion; therefore, this robot was not suitable for laparoscopic surgery.

The explanation is that, during conventional laparoscopic procedures, the surgeon is faced with specific constraints such as:
1. Loss of two degrees of freedom because of inflexible instruments and fixed points of insertion
2. Limited tactile feedback
3. Mirroring of hand movements
4. Variability of motion scaling caused by working with long instruments through fixed entry points
5. Inaccuracy during delicate reconstruction because of amplification of natural hand tremor
6. Dissociated hand–eye coordination and lack of depth perception secondary to two-dimensional visualization.

Master–slave robotic interfaces have been developed to overcome the inherent limitations of endoscopic surgery. Contemporary robots are able to reproduce the wrist
movements of the surgeon inside the body and therefore restore all degrees of freedom. The stability and precision, motion scaling and tremor filtering offer almost microsurgical performance. The architecture of all master–slave systems is similar: it consists of a surgical console that is nonsterile and placed remotely to the patient, the endoscopic stack, and three or four robotic arms.

This new generation of robots is represented by the two presently commercialized master–slave systems, concurrently developed by Intuitive Surgical and Computer Motion. Both devices are characterized by six degrees of freedom making them appropriate for laparoscopic surgery.

Fred Molland and Robert Young founded Intuitive Surgical in California in 1995. Their first prototype was the “MONA” robot. It was with this system that, on 3 March 1997, robot-assisted laparoscopic cholecystectomy was performed for the first time in history at the St. Blasius Hospital in Dendermonde, Belgium [15].

The Da Vinci robot derives from MONA and is characterized with reduced bulk enhanced ergonomy and improved tools. The Da Vinci offers three-dimensional vision via binocular endoscopic imaging.

Shortly afterward, the ZEUS system (Computer Motion, Goleta, Calif.) came onto the market in 1998. This system combined an AESOP robotic camera holder with two additional table-mounted robotic arms. Initially, the ZEUS system had instruments with only four degrees of freedom similarly to standard laparoscopic instruments, but in 2002 MicroWrist instruments gained FDA approval. The first generation of ZEUS offered only traditional two-dimensional views, but later the system was completed by three-dimensional glasses.

The advantage of the ZEUS is that it can be combined with the telecommunication system Sokrates to enable remote surgery over intercontinental distances. Since 1994 surgeons and computer scientists at European Institute of Telesurgery (Strasbourg, France) and telecommunication and robotic engineers from Computer Motion have joined in a common effort aimed at verifying the feasibility of surgery over long distances. This project was articulated in several steps that ended on 7 September 2001 with the performance of the first transcontinental robot-assisted laparoscopic cholecystectomy performed by Jacques Marescaux operating in New York on a patient in Strasbourg. This intervention entered into the history of surgery as “Lindbergh Operation” [16].

1.7.2.1 Clinical Experience with Master–Slave Systems in Urological Laparoscopy

The optimal candidates for robotic surgery are procedures where microsurgical precision and advanced reconstructive skills are necessary. In addition, the incidence of the urological disease should be high enough so that a consistent surgical volume is available to develop and standardize the technique, as well as acquire and maintain skills; therefore, presently the more often performed procedures in urology are robotic-assisted prostatectomy, radical cystectomy, pyeloplasty, and live donor nephrectomy.
1.8 Radical Prostatectomy

Robotic-assisted radical prostatectomy derived from the experience gained with its conventional laparoscopic counterpart (R. Gaston and T. Piéchaud, pers. commun.) [17, 18, 19–22]. The first Da Vinci-assisted radical prostatectomy was performed by Binder et al. in Frankfurt, Germany, in 2000. The surgical technique was first described and published by Abbou [23].

Although several European centers published small preliminary series, high costs and lengthy operative time limited the spreading of this technology [24–27]. In the United States, in the institute founded by Vattikuti, Meni Menon succeeded in accumulating sufficient experience to overcome the learning curve and develop a highly standardized procedure, thus diminishing operative time and costs. He reported a structured program for learning robot-assisted laparoscopic radical prostatectomy [28]. Menon had no previous laparoscopy experience; he was mentored by G. Vallancien and B. Guillonneau, who had a series of over 600 laparoscopic prostatectomy cases. The operative time for robotic procedure decreased with experience and after 18 cases and reached the operative time of conventional laparoscopic prostatectomy performed by the mentors. Menon's experience is at the origin of widespread use of robotic radical prostatectomy worldwide.

Since this initial study, the possibility of skipping the step of laparoscopic training has been further documented. Ahlering et al. confirmed that laparoscopically naive yet experienced open surgeons are able to successfully transfer open surgical skills to a laparoscopic environment after 8–12 cases using a robotic interface [29].

This explains the tremendous popularity of laparoscopic radical prostatectomy worldwide: It is estimated that 9,000 and 18,000 cases were performed in 2004 and 2005, respectively. In the few years since the initial robotic radical prostatectomies were reported, this procedure has emerged as the single largest indication for the use of the robot.

1.9 Radical Cystectomy and Urinary Diversion

The more complex robotic procedure in urology is radical cystectomy. The worldwide initial case was reported by Beecken in Frankfurt am Main, Germany [30]. The orthotopic Hautmann-type neobladder was formed completely intra-abdominally. The technique of radical cystectomy is based principally on the experience of radical prostatectomy; however, only anecdotal reports and small series of less than 25 patients are available worldwide [31–34].

1.10 Pyeloplasty

The experimental groundwork for robotic pyeloplasty was performed by Sung and colleagues in the porcine model using the Zeus robotic system [35]. Subsequently, the initial clinical experience with robotic Anderson–Hynes pyeloplasty was performed in Innsbruck, Austria, on a series of nine patients and reported by Gettman et al. [36]. The overall operative time was 139 min and the anastomotic time 62 min. Later, the
same group demonstrated in a comparative study that Da Vinci-assisted procedures are significantly shorter than standard laparoscopy [37].

1.11 Live Donor Nephrectomy

Laparoscopic donor nephrectomy successfully removes many disincentives to live kidney donation, resulting in an increased willingness of individuals to donate their kidneys. But the benefits are achieved only after a significant number of cases because of the complexity of procedures, time constraints, and the learning curve.

The first telerobotic simple nephrectomy in a human was performed by Guillonneau et al. using a Zeus robotic surgical system [38]. But live donor nephrectomy requires a more meticulous dissection. Furthermore, patient morbidity should be minimized particularly because this surgery is performed on otherwise healthy individuals.

In 2002, Horgan reported the first ten successful cases of robotic-assisted laparoscopic living donor nephrectomies using the Da Vinci system in the University of Illinois at Chicago [39]. Since this original report, in many centers where master–slave robots are available, performing robot-assisted live donor nephrectomy became a pragmatic choice.

1.12 Future of Robotic Surgery

Despite increasing interest and the development of procedures with proven safety and feasibility, many surgeons believe that robotics is “not ready for prime time” at most centers. This is explained by technical limitations and financial barriers.

It is not unrealistic to expect, however, that surgical robots will undergo a development similar to other fields of computing and telecommunications. The world’s first gigabyte-capacity disk drive, the IBM 3380, introduced in 1980, was the size of a refrigerator, weighed approximately 250 kg, and cost US$40,000. Such storage capacity is now available as a pocket-size USB drive and costs less than US$20. In many fields of contemporary medicine, routine practice has become inconceivable without computer-based systems. For example, surgeons consider computed tomographic data to be more reliable in making diagnoses than classic information such as physical examination, symptoms review, or history taking.

But robots go beyond the category of specialized surgical instruments. The emerging combination of high-precision robotic manipulators and new cross-sectional imaging techniques opens the horizon of presurgical planning with the help of a virtual model or the use of augmented reality during surgery.

References


