

The Evolution and Ergonomics of Robotic-Assisted Surgical Systems

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1. Introduction

A surgical robot has been defined as “a computer-controlled manipulator with artificial sensing that can be reprogrammed to move and position tools to carry out a range of surgical tasks” (Dasgupta et al, 2005). The first fully automated surgical device used in clinical practice was developed by Wickham (Harris et al, 1997) to resect prostates in the 1980's at Guy's Hospital in London. Currently, robotic devices are available in many surgical specialities fulfilling an increasing number of roles. The most commonly used is the da Vinci™ master-slave system (Intuitive Surgical, Ca, USA). The da Vinci™ system is widely available commercially. It is composed of three components: surgeon console, patient-side cart and image-processing/insufflation stack. Its stereoscopic vision, motion scaling and EndoWrist™ technology with seven degrees of freedom (DOF) are major advancements. By far the most common procedure performed with the assistance of the da Vinci™ system is laparoscopic radical prostatectomy. Other urological procedures performed using robotic assistance include cystectomy, nephrectomy, partial nephrectomy, pyelolithotomy and pyeloplasty. Other specialities adopting this technology include cardiothoracic surgery, gynaecology, and general surgery. Ergonomically ineffectual instruments and monophasic monitors in laparoscopy are linked to surgeon's musculoskeletal injuries and fatigue (Van Der Zee et al, 1997). Robotic surgery offers a different approach for the surgeon's position, with added visual benefits and increased dexterity. Research in the 'dry lab' environment has shown that the robotic techniques, though somewhat slower, offered more precision than conventional laparoscopy (Nio et al, 2002). Laparoscopy naïve surgeons have a shorter learning curve with robotic-assisted techniques compared with equivalent laparoscopic tasks. Research is ongoing in the assessment of fatigue when using robotic-assisted, laparoscopic and open techniques (Elhage et al, 2007). It is suggested that the improved ergonomic conditions offered by robotic systems may allow surgeons to operate more efficiently and with greater precision. As a result patients may have less morbidity and a shorter recovery time.

2. The Evolution of robotics in surgery

2.1 History of surgical robots

Leonardo Da Vinci designed the first robot. It was an automated knight capable of performing basic movements to entertain his patrons (Rosheim, 2006). However, it was not until late in the 20th century that robotic technology became widely available for medical applications. In the 1980's researchers explored the potential of robotics in surgery. Several investigative projects started in the United States (US) and Europe, some independently and some as collaborative work.

2.1.1 Neurosurgery and orthopaedic systems

Initially the greatest potential for robotics was anticipated to be in the fields of neurosurgery and orthopaedics due to their defined parameters and devices such as the ROBODOC (Integrated Surgical Systems, CA, USA) were developed. The hypothesized advantages were: an increase in the three-dimensional (3D) accuracy, increased reproducibility of repeated procedures, increased precision of movements by scaling the motion of the surgeon several times and the ability to perform surgery from a distance (telesurgery). Neurosurgery became a suitable platform for testing early robotic systems because the cranium is a rigid container with fixed landmarks that can be used as data points. Thus stereotactic frames were developed in the late 1980's for the purposes of cranial biopsy and were combined with robots such as the Unimate Puma (Programmable Universal Machine for Assembly, CT, USA) and neuronavigator wand (ISG Technologies, ON, Canada). These consist of robotic arms moved by a surgeon combined with a computer capable of 3D imaging.

A number of robotic frames exist that can assist with surgical procedures. The PUMA 200 robot has been used in the resection of mid-brain tumours in children (Drake et al, 1991), while the Minerva device allows neurosurgical needle placement whilst the patient is within a Computerised Tomography (CT) scanner (Glauser et al, 1995). A frameless image-guided computer controlled system has been launched, the Neuromate (Integrated Surgical Systems), which includes a pre-surgical planning workstation which subsequently interacts with the surgeon during surgery. In orthopaedics, where the bones allow fixed device positioning due to their rigidity, several robots have been developed to perform accurate reaming and cutting of bones to facilitate the insertion of prostheses. By combining increased precision with a digitally stored osseous image, bones can be reamed to provide optimal contact with prosthetic stems such as in uncemented total hip replacements, e.g. ROBODOC (Integrated Surgical Systems) (Cain et al, 1993). This robot, first produced in 1992, is designed for use in primary and revision total hip replacement as well as in total knee replacement. It consists of a preoperative planning workstation (Orthodoc) and a five-axis robotic arm with a high-speed burr as an end effector, which mills the femoral canal for the selected implant chosen beforehand. Orthodoc is used to precisely plan surgery by integrating CT scans of the patient to allow accurate pre-operative implant selection. Clinical studies in the USA using ROBODOC with 65 patients, and with 900 patients in a German study show that the robotic system produces a radiographically better fit and positioning of the implant, and eliminates intra-operative femoral fractures (Bargar et al, 1998). It is vital that this generation of orthopaedic robots are built with safety constraints, as seen with the Acrobot, which allows motion in pre-programmed regions, by the surgeon back-driving the robot motors, while preventing motion in prohibited areas. This active

constraint robot (or Acrobot) is programmable and has potential for minimally invasive procedures such as unicompartmental knee replacement (The Acrobot company, 2007).

2.1.2 Automated surgical robotic system

One of the pioneers of robotic surgery was John Wickham, a urologist from Guy's Hospital. He developed the first clinical robot in urology, the PROBOT in 1989. Wickham worked on a transurethral resection of prostate (TURP) robotic frame in a joint project with the mechanical engineering department at Imperial College, Guy's Hospital and the Institute of Urology in London (Harris et al, 1997). The device attempted to perform robotic TURP. As the prostate gland is a relatively fixed organ and the procedure requires repeated similar movements TURP is suited for total robotic control. The frame is constructed to support a six-axis Unimate Puma robot combined with a Wickham Endoscope Liquidizer and Aspirator. The liquidiser blade rotates at 40,000 rpm and initial clinical trials in patients, following successful tests on prostate-shaped potatoes, showed that the PROBOT assisted TURP to be safe, feasible and rapid. Further trials using the PROBOT for TURP resulted in an improvement in patients' symptoms (Harris et al, 1997). One important concept in the design was that the tool could cut only within an ultrasound guided, physically restricted volume, making the device intrinsically safe. Although never mass produced, this was the first truly automated robotic device used clinically, as opposed to the subsequent master-slave devices which were developed in the United States.

2.1.3 Master-Slave systems

These devices started in the 1980's as the telepresence system and were collaborative efforts between the National Aeronautics and Space Administration (NASA), which had the expertise in virtual reality, and Stanford Research Institute headed by Philip Green (Satava, 2002). Several years passed before the next generation of robotic devices became available. Computer Motion (Berkeley, CA, USA) first introduced the Automated Endoscopic System for Optimal Positioning (AESOP™) in the mid-1990's. AESOP controls an endoscope in response to the surgeon's commands, using either voice, foot or hand control. By imitating the form and function of a human arm, it eliminates the need for a member of the surgical team to manually control a laparoscopic camera. With precise and consistent movements, AESOP gives the surgeon direct control over a steadier operative field of view. AESOP responds to a vocabulary of 23 commands and was the world's first US Food and Drug Administration (FDA) -cleared surgical robot capable of assisting in minimally invasive procedures (FDA, 1999). Since its introduction, AESOP has assisted in more than 45,000 minimally invasive surgical procedures in more than 350 hospitals internationally. It is now regarded as a standard tool in performing laparoscopic radical prostatectomy and enables independent operating. Laparoscopic images with the AESOP are steadier with less camera changes and inadvertent instrument collisions compared with an inexperienced human assistant (Kavoussi et al, 1995). Another development was the EndoAssist (Armstrong Healthcare, High Wycombe, UK) a free-standing laparoscopic camera manipulator, controlled by infrared signals from a headset worn by the surgeon. It was also introduced in the 1990s (Finlay, 1996). It is considerably less expensive than the AESOP but takes up more space in the operating room.

The first master-slave system was also developed by Computer Motion, the ZEUS Robotic Surgical System, which allowed the surgeon to control laparoscopic instruments at a

console remote from the operating table. It was first used on humans in 1998 and in 2001 it allowed a surgeon in New York to perform a laparoscopic cholecystectomy on a patient in Strasbourg, the first reported transatlantic telesurgery (Marescaux et al, 2001). The ZEUS system has now been phased out as a result of the merger of Computer Motion with Intuitive Surgical (Sunnyvale, California, USA) in 2003 paving the way for the development of da Vinci master-slave systems which now dominate the field of robotic-assisted surgery.

2.1.4 Telerobotic surgery and telementoring

An Italian group led by Professor Rovetta performed a number of experiments investigating the possible applications of telerobotics and reported to have carried out the first telerobotic surgery in 1995; a prostate biopsy (Rovetta & Sala, 1995). The field of telerobotics in urology, in particular percutaneous nephrolithotomy (PCNL), has been led by L.R. Kavoussi, D. Stoianovici and the Urobotics team at Baltimore. The percutaneous access robot (PAKY-RCM) was initially developed in 1996 and was superseded by the production of the Tracker in 2003. This can be mounted on the operating table. It has six DOF and can be used with fluoroscopy or CT guidance to improve the accuracy of needle placement. This can provide a precise and reliable method of routinely performing the preliminary step in PCNL or tissue biopsy and can be controlled remotely. The Baltimore group has also telementored several procedures around the world including laparoscopic adrenalectomy, radical nephrectomy, varicocelelectomy and renal cyst ablation (Janetschek et al, 1998), (Lee et al, 2000), (Frimberger et al, 2002). The first randomised controlled trial of trans-Atlantic telerobotics was performed between Guy's and Johns Hopkins Hospitals with robotic needle punctures during PCNL into a kidney model controlled remotely. The robot took longer to perform the procedure but was significantly more accurate than a human. There was no difference between trans-Atlantic and local needle insertions with regard to either time or accuracy (Challacombe, et al, 2003)

3 Technology of robotic surgery

3.1 The da Vinci systems

The daVinci is the most advanced master-slave system developed until now. It is not an autonomous robot. The surgeon sits remote from the patient and controls three or four da Vinci robotic arms which are docked through laparoscopic ports at the patient side. The system has three components: (a) a surgeon console, (b) a patient-side cart and (c) an image-processing or insufflation stack. The three-dimensional view from the endoscope is projected in the console at 6-10 magnification. The surgeon's thumb and forefinger control the movements of the robotic arms. Foot pedals allow control of diathermy and other energy sources. Motion scaling enhances the elimination of tremor, allowing very smooth and precise movements. The robotic arms are mounted on the patient-side cart, one of which holds the high-resolution three-dimensional endoscope. Specialised EndoWrist™ (Intuitive Surgical, California, USA) instruments are mounted on the remaining arms. The image-processing/insufflation stack contains the camera-control units for the three-dimensional imaging system, image-recording devices, a laparoscopic insufflator and a monitor allowing two-dimensional vision for the assistants. The three-dimensional vision, enhanced magnification, motion scaling and most importantly the endowrist technology

makes easier for the operating surgeon to perform complex laparoscopic procedures (Murphy et al, 2006).

3.2 Current application

Since it became commercially available, the da Vinci system has been used to perform procedures in several surgical specialties including urology, abdominal, thoracic, cardiac, and gynaecological surgery, ranging from complex cancer operations to organ transplantation. However the most commonly performed procedure using the da Vinci systems is radical prostatectomy for localised prostate cancers. Robotic radical prostatectomy was first described by Menon and five years after the introduction of da Vinci system it is expected to be used to perform 48000 cases or 63% of all radical prostatectomies in USA by the end of 2007 (Menon, 2001, 2007). The risks and complications of radical prostatectomy on patients are well recognised and include bleeding and the need for blood transfusion, impotence, urinary incontinence and incomplete clearance of cancer. The early reports on the clinical and functional outcomes suggest that the new technique is as good as the standard open surgical technique in terms of cancer clearance, and may be better in terms of need for transfusion, recovery time, sexual potency and urinary continence (Ficarra et al, 2007). Another operation that is increasingly gaining acceptance in clinical practice is the robotic radical cystectomy; a new technique has been described by Dasgupta (Raychaudhuri et al, 2006). However the lack of randomisation and long term outcome does not allow definite conclusions regarding the superiority or otherwise of the new robotic technology. Other procedures performed using the da Vinci robot are still evolving and results are still scarce.

4. Ergonomics and robotic assisted surgery

4.1 Basics of ergonomics in modern surgery

Ergonomics is derived from the Greek *ergon* (work) and *nomos* (laws). Definitions vary, Oxford dictionaries define it as 'the study of people's efficiency in their working environment' (Oxford English Dictionary, 1998). The international ergonomics association (IEA) has a more specific approach and defines it as 'the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data and methods to design in order to optimize human well-being and overall system performance'. (IEA website, 2007). IEA divides ergonomics into domains of specialisations. Organisational ergonomics deals with human interaction with work systems and policies. Cognitive ergonomics concentrates on the human mental ability to cope and interact with various work conditions. Physical ergonomics is the study of the effect of working conditions on human body. Interest in ergonomics in surgery has become more important following the introduction of minimal access surgical instruments and systems. Factors affecting efficiency of surgery include access, vision, manoeuvrability and the ease of using instruments. Open surgery provides the surgeon with excellent exposure, direct vision of the operative field and user-friendly instruments. Minimally-invasive surgical techniques including laparoscopic surgery offer significant advantages for patients in terms of lower morbidity and reduced recovery times. Factors affecting efficiency of surgery include access, vision, manoeuvrability and the ease of using instruments. But these instruments are not always as easy to manoeuvre as open surgical tools. Minimally-invasive surgical techniques offer significant advantages for

patients in terms of lower morbidity and reduced recovery times. By contrast to open surgery, the technical challenges to laparoscopic surgery may lead cumulatively to specific ergonomic problems for the surgeon. Laparoscopic surgeon has to learn to adapt to monoscopic vision in 2 dimensions (2D). Tendick et al found that 2D monoscopic display decrease operator accuracy and increase movement time. Manipulation of long laparoscopic instruments causes a number of problems. There is a fulcrum effect at the point of trocar insertion through the abdominal wall, where hand movement to the right produces a movement to the left at the tip of the instrument at the operative field. Instruments are long and move in a cone-shaped way with the tip of the cone at the trocar's insertion point of the abdominal wall. Arc-like movements of the upper extremity are necessary to produce small movements of the end effector. Laparoscopic surgery allows 4 DOF at the operative site restricting manoeuvrability to great extent. During laparoscopic surgery the majority of the surgeon's movements are at the level of the hands, wrists and, to a lesser degree, the shoulders. The rest of the body is in an upright position which may be responsible for the neck and back discomfort associated with laparoscopy. A team from Sacramento video taped laparoscopic surgeons while operating and noted the awkward upper extremity movements of the surgeon and a static trunk and neck position (Nguyen et al, 2001), Berguer et al studied various types of laparoscopic handles. They recorded the positions and the electromyographic (EMG) signals of the wrists and forearms of surgeons using the instruments and found that higher degree of muscles contractions are required compared to open surgery and with laparoscopic handles often extreme positions of flexion and ulnar deviation at the wrist are required to perform a task (Berguer et al, 1998). Hemal et al reported many musculoskeletal injuries associated with laparoscopic surgery. When asking 131 laparoscopic surgeons 22% complained of eye strains, 18% of arm, shoulder, and finger numbness. Neck, back and forearm pain were among the common complaints (Hemal et al, 2001). These problems increase the overall fatigue of the surgeon and restrict the number of minimally invasive procedures that can be done by single surgeon in a given operative session.

The master-slave robotic surgical systems may help resolve some of the ergonomic problems described above. The surgeon is seated at a console remote from the patient, providing a much more ergonomic posture than that of the traditional patient-side surgeon. The finger-tip controls allow "intuitive" rather than "fulcrum"-type control over the laparoscopic instruments, thereby reducing fatigue in the upper extremity and neck. The complex surgical tasks e.g. (suturing) are made easier by the EndoWrist technology which allows an overall 7 DOF as compared to 4 DOF for laparoscopy. Another advantage is the 3D stereoscopic vision with enhanced magnifications and motion scaling of surgeon's hand movements down to the site of operation. This allows the surgeon to feel almost immersed in the operative field. Jourdan et al conducted a study where they compared tasks performed under either monoscopic or stereoscopic vision and found that stereoscopic vision provides a significant advantage (Jourdan et al, 2004). Another aspect of robotic assisted surgery was studied by a team from Amsterdam; they compared laparoscopy and robotic assisted surgery by asking expert laparoscopists and medical students to complete validated tasks. The students who were laparoscopy and robotics naïve required more time to perform equally accurate tasks compared with experienced laparoscopic surgeons (Nio et al, 2001). In a more recent study, Berguer and Smith studied the physical and mental workload of laparoscopic and robotic assisted surgery during a surgical conference. Surgeons performed simulated tasks while the investigators recorded errors and EMG

signals for physical workload, and assessed skin conductance for mental workload. They found that robotic assisted technique was slower and less precise than laparoscopic for simple tasks; however they were equally fast for complex techniques and possibly less stressful (Berguer & Smith, 2006).

We are currently comparing the impact of physical activity of both techniques on surgeons in a dry lab setting. Standard tasks are performed using open, laparoscopic and robotically assisted techniques. EMG sensors record muscular activity; motion capture cameras capture postural variation. An analysis of the obtained data will allow objective comparison of these techniques and will help to understand the impact on surgeons. (Figure 1)

4.2 Advantages and disadvantages

As we have seen in previous sections, robotic surgery offers accurate dissections, less blood loss, quick recovery of patient; it probably is more ergonomically effective compared to other minimally invasive techniques. However this technology is still out of the reach of many healthcare institutions, especially the public sector due to the high initial costs (£750,000), maintenance (£70,000/year) and the cost of consumables. An important disadvantage is the lack of tactile feedback. The surgeon is not able to feel for the tissue however surgeons learn to adapt to visual feedback to compensate. Research in this field is still inconclusive and bridging this problem would take robotic surgery to a higher level. Other disadvantages are summarised in table 1 below.

4.3 Future

Recently Intuitive Surgical introduced the da Vinci S which has improved maneuverability, faster set up time, and improved video display. The next generation of da Vinci is expected to have a smaller console and surgical cart, and possibly haptic feedback technology. Preoperative imaging e.g. CT, Magnetic Resonance Imaging (MRI) may be integrated in the system to help the surgeon plan surgery. A new concept of robot built with non-magnetic or dielectric materials is being developed by the team from Baltimore led by Stoianovici. This development will allow the compatibility of robotics with MR imaging, thus allowing MRI guided robotic procedures (Muntener, 2006). However the most exciting next generation of robots are nanorobots which are micron small robots which could be able to deliver targeted gene therapy (Murphy et al, 2006). Robotic surgery is in its infancy and certainly is growing fast.

Advantages	Three-dimensional visualisation Enhanced degrees of freedom No fulcrum effect Motion scaling Elimination of tremor Reduced fatigue Ergonomic positioning
Disadvantages	Expensive capital and running costs No tactile feedback Reduced trainee experience Set-up times lengthy

Table 1. Advantages and disadvantages of robotic surgery (Murphy et al, 2006).

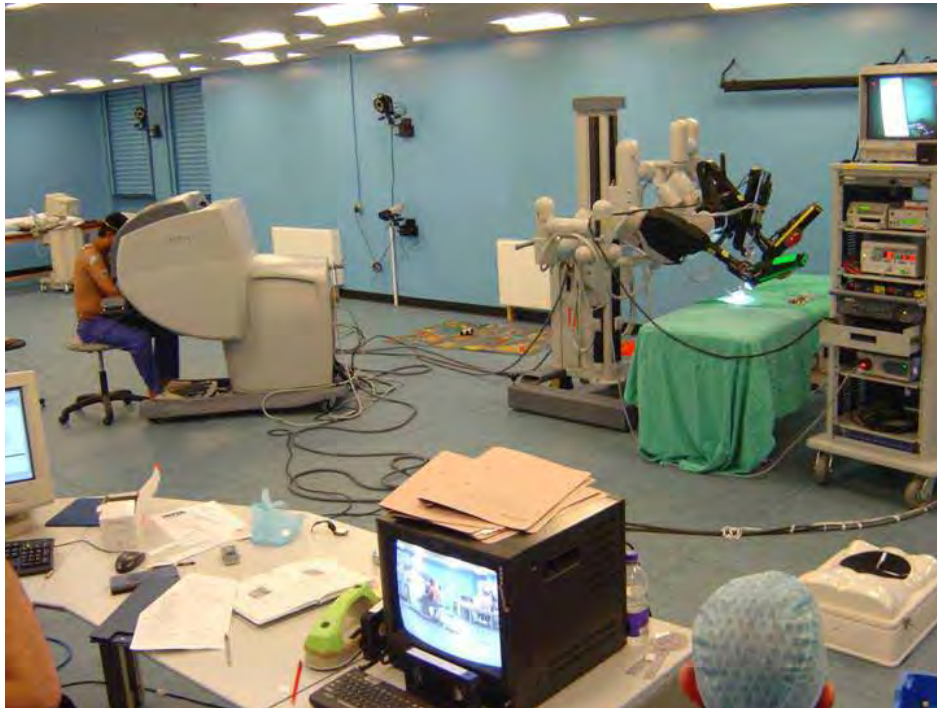


Fig. 1. Ergonomic assessment of da Vinci system in Gait Lab.

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