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Review

Robot-assisted surgical systems: a new era in laparoscopic surgery

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The introduction of laparoscopic surgery offers clear advantages to patients; to surgeons, it presents the challenge of learning new remote operating techniques quite different from traditional operating. Telemanipulation, introduced in the late 1990s, was a major advance in overcoming the reduced dexterity introduced by laparoscopic techniques. This paper reviews the development of robotic systems in surgery and their role in the operating room of the future.

Key words: Robotics – Minimal invasive, surgery – Telemanipulation – Laparoscopy

The widespread introduction of laparoscopic techniques during the last decade of the 20th century was one of the most prominent changes in modern surgical practice. Many open surgical procedures, such as cholecystectomy, inguinal hernia repair and oesophageal reflux surgery, have been reduced to minimally invasive interventions. This has benefits for the patient in a shorter postoperative stay in hospital, less pain, a better cosmetic result and a faster return to normal activity.

Despite a growth in the range of laparoscopic procedures, surgeons remain hampered by the limitations imposed by remote operating. The recent introduction of computer-aided instruments, such as robotic surgery systems, has the potential to revolutionise endoscopic surgery by allowing surgeons to use their traditional open surgery skills for laparoscopic operations.

Shortcomings of current endoscopic surgery techniques: the base for new developments in surgery support systems

In open procedures, the surgeon has unlimited flexibility in positioning his body, elbow, wrist and fingers; the operative field may be approached from various directions, and the surgeon controls his actions by visual and tactile feedback.

During endoscopic surgery, the problem of working with long instruments through fixed entry points and looking at a screen greatly reduces this feedback. The surgeon's actions are further compromised by limitation of the movement of the instruments to only four degrees of freedom (DoF). The angular displacement of the instruments inside the body following a movement of the surgeon's hand hereby varies according to the length of the instrument that is introduced into the body. The hand–eye co-ordination is further reduced by the loss of the eye–hands-target axis, compromising normal oculovestibular input.[1] Basic surgical manoeuvres like suturing, therefore, demand highly developed technical skills which the surgeon needs to learn.

Looking at a two-dimensional screen, surgeons are handicapped by the loss of the visual perception of depth and, additionally, by the need for a human assistant to hold and move the camera. The latter causes discomfort, because the field of view is no longer under the surgeon's own control. Orientation errors and unstable camera control may compromise the smoothness of the operation.

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Although many abdominal operations can be performed laparoscopically at this moment in time, performance of complex minimally invasive surgery is in the hands of a limited number of experts. Therefore, researchers have started to develop new tools for laparoscopic surgery to minimise the unsatisfactory aspects of the process. The launch of robotic telemanipulation systems heralds this development.

Robotic telemanipulation systems: history and current status

Reduced dexterity and impaired visual control were considered the major burdens of endoscopic surgery and initial attempts in developing robotic support systems aimed at enhancing the surgeons' control of the instruments and of the endoscope. The first applications of robotics in surgery were in the field of camera guidance systems.

In 1994, the American company Computer Motion was the first to obtain FDA approval for the use of the AESOP® (Automated Endoscopic System for Optimal Positioning) robot arm in the operating theatre. This camera arm mimics the function of a human arm. It was designed to offer the surgeon direct control over the camera system by means of a foot pedal or voice control. The voice recognition system enables voice activation of the camera following previously recorded voice commands. The AESOP arm provides the surgeon with a steady and flexible view of the operative field, independent of the skills of a human camera assistant.[2,3]

At the same time in Germany, the Tiska® endoarm (a passive system) was developed which allowed a stable optic positioning by means of electromagnetic friction. This was controlled by a foot-pedal. The arm could also be used as an instrument retractor.[4] The point of trocar insertion into the abdominal wall is fixed protecting the patient against excessive forces at that point.

The Fips® endoarm is an example of an active camera system where the surgeon moves this camera system either manually by a finger ring joystick, clipped on the handle of an operating instrument, or by voice.[5]

In 1998, the British firm Armstrong Healthcare launched the Endoassist® robotic camera assistant for laparoscopic surgery. It moves the camera in synchrony with the surgeon's head movements making intuitive control of the visual field possible. The camera only follows when a foot switch is pressed, allowing the surgeon to make head movements freely at all other times.[6]

Whilst developments in imaging systems clearly progressed, dexterity problems remained a crucial problem. In the early 1990s, the concept of a master–slave telemanipulator was developed. This concept required the surgeon to control a manipulation system from a master console remote from the patient. A computer placed between the surgeon's hands and the end-effectors of the instruments, uses computing power to support the surgeon's dexterity. The surgeon moves two master devices made to resemble surgical instruments at the console, and each motion is translated to the robotic arms which scale down the movements at the end of the instruments inside the patient's body. The robotic slave arm follows all commands of the master arm in a natural way, comparable to manipulation in open surgery.

The original goal of developing these telemanipulators was to enable telesurgery. This would allow surgeons to operate on patients from a remote location thus avoiding hazardous environments, such as a battlefield, or inaccessible places, such as outer space. It would also allow them to perform surgery on patients who carry life-threatening infections. The US Federal Government supported research in this field at Stanford Research Institute and, in the early 1990s, the first master–slave manipulator for surgery was developed. Only four DoF were available in this instrument and, since it filled almost half the operating theatre, it was not a feasible option.[7] In 1994, the technology was licensed to the company Intuitive Surgical.

In Germany in 1992, the ARTEMIS® (Advanced Robotic Telemanipulator for Minimally Invasive Surgery) was made. This was the first system that provided instrument mobility with six DoF. It integrated the Fips® Endoarm with a conventional technical telemanipulator, mastered by a joystick.[8] The prototype made it to the experimental phase, but neither commercial production nor clinical application was achieved.[9]

At this moment, two US companies have received European Union clearance for clinical application of their telemanipulation systems for general and cardiac surgery. Intuitive Surgical and Computer Motion received FDA clearance in 2000 for general surgery applications with the da Vinci® and Zeus™ telemanipulation systems. Both systems were initially developed for cardiac applications but are stll waiting for complete FDA clearance for these procedures.

The Zeus™ robotic system (Fig. 1) consists of three separate robotic arms attached to the sidebars of the operating table. Two arms hold and manipulate a variety of surgical instruments, and one arm handles the camera. The surgeon steers the surgical instruments through two egg-shaped control devices. The Zeus™ system has recently been integrated within the Hermes® system, which gives the surgeon direct control of endoscopic add-ons. The camera, insufflator, light-source and other additional instruments are adjusted by voice or by a foot pedal. Three-dimensional (3D) vision is incorporated, but requires the use of goggles with shutter glasses.

The da Vinci® robot (Fig. 2) consists of a master console, where the surgeon sits, looking at a 3D binocular display of the operative field. A three-armed robot cart is at the operation table and the middle arm carries the two-channel optical system. Two independent video images are transmitted to the binocular where they merge thus providing a true 3D image of the operative field. The camera is controlled by the Navigator™ system, and enables the surgeon to pick up and move the camera by foot pedal. During the camera movement, the slave instruments stay in position. A second foot pedal freezes the instruments, which allows repositioning of the controllers and forearms to an ergonomically favourable position. The control devices have a configuration similar to regular surgical instruments. The surgeon's movements

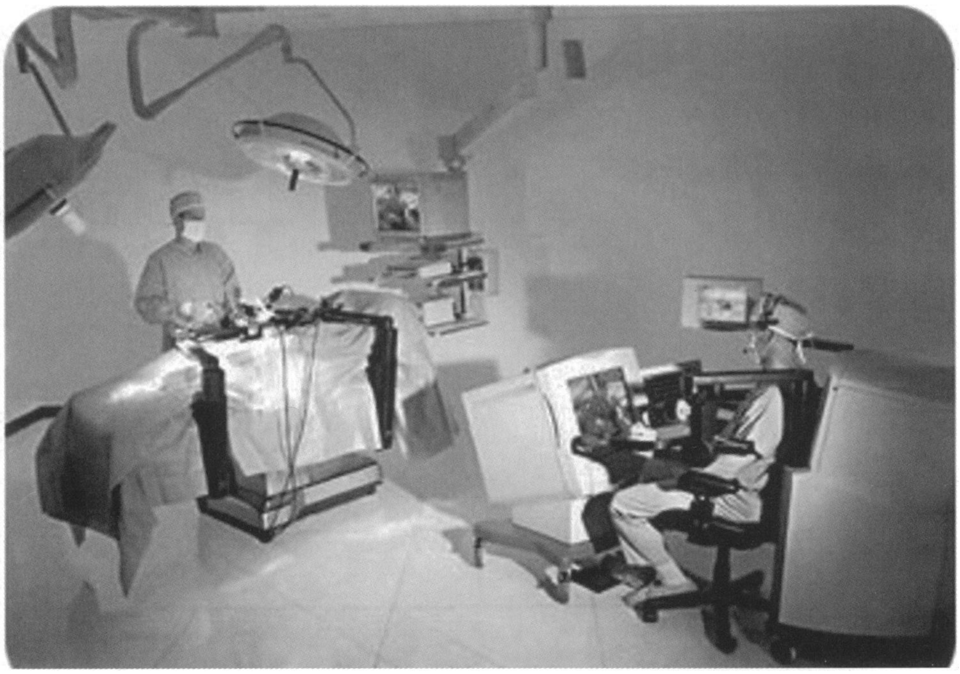

Figure 1 A surgeon manipulating the Zeus™ system. The surgeon is using two manipulators and his voice in order to control the three arms of the system.

Figure 2 The da Vinci® system. The surgeon is seated behind the console, the three-armed chart is located next to the operation table. The surgeon's hands and view are pictured in the lower right quadrant.

Table 1 *Number of robotic procedures performed*

	Intuitive surgical da Vinci® system	Computer motion Zeus™ system (estimated)
General surgery	2220	100
Thoracic/vascular surgery	1993	570
Gynaecology/urology	1145	270

are transposed to the tips of tiny instruments, where the Endowrist® system provides the surgeon with six DoF inside the patient's body. Control mimics the natural movements of open surgery.

The intuitive control of movements is improved in the da Vinci® system by the integration of both the visual system and manipulators in the master console thus restoring the eye–hand target axis. The system goes into stand-by mode when the surgeon moves away from the 3D binoculars.

The major advantage of these newer master–slave robotic systems is the introduction of extra decrees of freedom at the end of the instruments, allowing surgeons to manipulate in a manner similar to that of open surgery. The Zeus™ offers five DoF the da Vinci® offers six, both complete with an intuitive control mechanism. In addition, the unnatural opposite response of the instruments is corrected by the robotic telemanipulation systems. Tremors and trocar resistance are eradicated by the man–machine interface. The digital processing allows the scaling down of the surgeon's hand movements to a level where microvascular procedures are feasible. The ergonomic and reduced fatigue features will be a great advantage.

The first operation reported using a robotic telemanipulation system was a laparoscopic cholecystectomy performed on 3 March 1997 at the St Pierre Hospital in Brussels, Belgium.[10] Others have followed in the last few years, not only in general surgery but also in cardiac surgery, gynaecology and in urology. More than 1000 procedures have now been performed with the da Vinci® system and almost the same number with the Zeus™ (Table 1). Instruments are being installed in hospitals in Europe and the US.

Robotic surgery systems: future perspectives

The benefits of robotic telemanipulators in the operating room are apparent, but many challenges remain. Proof of benefit for patients has yet to be determined. One of the major points of criticism is the lack of tactile feedback from the operating instruments. Currently, this is only partly compensated for by the 3D visual feedback.

The time to set up the equipment is acceptabe for complicated surgery but still too long for daily practice. Whilst experience improves this, the size of the system compromises the proper positioning of the robot in relation to anaesthetic equipment, X-ray facilities, and space to allow the surgeon close to the patient. Integration of the systems into the design of the operating room by attachment to the ceiling or operating table may help.

The other potential application of this technology is in surgical skills' training. Virtual reality training programs can be integrated in the system computers and two consoles can be coupled to allow an experienced surgeon to adjust and correct the movements of the trainee. The tutor is able to take over the instruments and show the resident the way to do things correctly. Surgeons that currently use robotic telemanipulators report a significant learning curve in using the system.[11] A double console teaching set-up could considerably diminish this.

Robotic telemanipulation systems potentially offer great benefits for endoscopic surgeons, while enhancing ergonomics, providing additional DoF, three-dimensional visualisation and possibilities for surgical skills training. Challenges remain in implementing these systems in daily practice. In the upcoming years surgeons will have to prove that these systems will offer patients significant benefits that outweigh the additional efforts and costs that are still embedded in their usage.

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