Robot-Assisted Surgery: A Review

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Abstract

Robot-assisted surgery is the latest technology to be introduced into the operating theatre. It offers several advantages over conventional surgery, including greater spatial accuracy, increased dexterity and precision, reliability and reproducibility, measurable cost savings and ultimately better patient outcomes. However, its introduction into the surgical suite has been slowed by some of its drawbacks, such as large initial cost outlay, diminished operative field-of-view, decreased tactile feedback, and reduced flexibility to respond to major complications. As technology improves, it is likely that many of the disadvantages will be remedied and robots will play a greater role in future surgeries, as well as in other areas, such as tele-surgery and surgical education. However, before robotics can be adopted by all surgeons, its economic and patient benefits must be demonstrated by more extensive clinical trials.

As technology becomes increasingly complex and powerful, it becomes a greater part of everyday life; medicine is just one of the areas that is being revolutionized by this technological invasion. From the urine-analyzing toilet in development in Japan to the complex tools used in the human genome project, technology assists all facets of medicine from diagnosing patients to elucidating the constituents of the human genetic code. One area that has caught great media interest in recent years is the use of robots in surgery. This article will briefly outline the history of the field, discuss the basic concepts of robot-assisted surgery, and explore some of the advantages, disadvantages, and future directions of this advancing area.

History

The success of pre-programmed and remote-controlled industrial robots in the 20th century, in terms of precision, cost-savings and superior performance, spurred the development of medical robots as a tool to enhance a physician’s abilities. These developments led to their entrance into various fields including rehabilitation, laboratory automation and surgery.1 Surgical robotics was first introduced in the 1980s into neurosurgery and orthopedic surgery, due to the ability of the respective organ systems involved to provide fixed landmarks and the precision required in their respective procedures – manipulation of brain tissue in the former and precise cutting and coring of bone in the latter. Promising results in these fields subsequently led to the introduction of robotics into many other specialties including urology, otolaryngology, laparoscopic surgery and cardiac surgery. Telesurgery, an extension of robotic surgery involving the surgeon being physically separated from the operating robot, was first considered by the U.S. military as a way of performing battlefield operations from behind battle lines.2 In 1992, it was introduced as a concept in civilian medicine.3 Since then, several such robotic prototypes have been built that involve the surgeon operating the robot from a few metres away using a computer console and issuing commands by voice, joysticks and mock instruments. Clearly, surgical robotics have evolved a great deal in the last 20 years; to fully appreciate their impact on surgery, it is first necessary to consider some of the basic principles.

Basics

In order to understand surgical robotics, it is necessary to understand the most basic aspect of robotics – what is a robot? The Robot Institute at Carnegie Mellon University defines a robot as “a reprogrammable multifunctional manipulator designed to move materials, parts, tools, or specialized devices through various programmed motions for the performance of a variety of tasks.”4 Surgical robots are better termed “robotic devices” that share some of the features of the classical robot – they are highly variable in appearance, size, and function, as well as method of operation. Some are handheld while others are fixed to a support. Some perform a pre-determined operation upon command, while others respond by mimicking and enhancing a surgeon’s hand movements – movements that are made on mock instruments or joysticks several feet away.

Surgical robots can be divided into two broad classifications – active and passive. The surgeon provides the physical force required to operate a passive robot, while an active robot does not require human power and is often computer-controlled.4 This affords active robots a degree of autonomy in performing their tasks that makes many of them intrinsically unsafe – that it, they have the capacity to execute unsafe motions. The earliest robots were both passive and intrinsically safe, but more advanced systems are active and not intrinsically safe; it is important to note that many robots can switch from active to passive mode over the course of the surgery.

Robots are currently used in many areas such as neurosurgery, orthopaedic surgery, urology, otolaryngology, and in endoscopic procedures such as lung resections and coronary artery bypass grafts (CABG).5-7 Some of these operations involve preoperative imaging with CT or MRI, and subsequent three-dimensional reconstruction to give an accurate view of the organ of interest. Certain operations (e.g., prostatectomy) utilize intrinsically safe robots, while others (e.g., stapedotomy) do not. Prostatectomies have been performed...
transurethrally by a robot developed at Imperial College in London, which first images the prostate by ultrasound. The ultrasound tool is then replaced \textit{in situ} by a cutting tool to ensure that the cutting field and the imaged field are identical. This restriction on the robot’s movement makes this active robot an intrinsically safe one. Performing a stapedotomy involves removing most of the stapes and drilling a hole through its footplate. However, drilling through the footplate runs the risk of puncturing the oval window on which the footplate rests. The robot that performs this procedure tracks the cutting force and the work applied by the motor to determine when drilling should stop. Since the thickness of the stapes is variable, the amount of drilling that the robot performs cannot be preset. Consequently, the robot needs to make its own decision as to when to stop; an error can lead to a ruptured oval window and severe inner ear damage. Therefore, this active robot is not intrinsically safe.

Advantages and Disadvantages

Robot-assisted surgery has many advantages over conventional surgery: greater spatial accuracy, dexterity and precision, reliability and reproducibility, and ultimately better patient outcomes. By their very nature, computers have better three-dimensional spatial acuity than do humans. They are able to synthesize slices from a CT or MRI scanner into a three-dimensional organ, and are more precisely able to determine their own location relative to the organ. This has tremendous benefit in all areas of surgery, particularly neurosurgery. Currently, by coordinating a surgical robot with an MRI scanner, a surgical tool can be placed to within 0.5 mm of a lesion in the brain, compared to an accuracy of 1 mm when not coupled with the imager. The greater accuracy generated by MRI-guidance can lead to a more precise repair of the lesion. In addition, the robot can also plan the best route to follow to position the tool in the required location, thus minimizing collateral damage and resulting morbidity.

Several factors contribute to the greater precision obtained when using a robot. It can be used to filter out a surgeon’s hand tremor, enhance a surgeon’s motions and perform accurate microscale movements that are otherwise impossible for a human to perform. In addition, with the advent of voice-recognition technology, the surgeon no longer needs a human assistant to control an endoscopic camera, such as during a thoracoscopic lung resection or a laparoscopic cholecystectomy. Studies have shown that a camera controlled by the surgeon’s voice instead of an assistant responding to the surgeon has the advantage of requiring significantly less field-of-view corrections and camera cleanings. As issuing commands to move the camera is a distraction to the surgeon, the advantages of using a robot-controlled camera whose movements require less correction are obvious. However, the disadvantages of this option include a longer setup time in one study and the inability of the robot to anticipate the surgeon’s next move — something an experienced human assistant would be able to do.

Reliability and reproducibility are also advantages inherent to the fact that robots are automatons. Given an algorithm, they will perform that algorithm precisely every time they are used. As a result, their behaviour is predictable and their actions are reproducible. It is of note that even the more advanced robots that are not intrinsically safe perform their actions in a predetermined manner and will perform a task identically on a given object every time. Clearly, such a degree of reproducibility is not achievable by humans.

Lastly, and perhaps most importantly, the use of robots can improve patient outcomes. Greater precision in operating on tissues such as the brain causes less damage to uninvolved tissues and thus reduced morbidity. In addition, robots allow endoscopic techniques to be used in areas previously thought to be inaccessible. Surgeons at the London Health Sciences Center at the University of Western Ontario recently performed the first closed-chest, beating-heart CABG in the world using the Zeus™ system; Figure 1 shows how such a revascularization is achieved in an ex vivo setting with the heart in a model rib cage. The surgery was performed with small pencil-sized incisions through which a camera and instruments were inserted into the patient’s thorax. In addition to bypassing one vessel, some of the surgeries performed involved a second surgeon simultaneously revascularizing another vessel using angioplasty. Figure 2 shows several aspects of the da Vinci™ robot, another system that has been used to perform endoscopic cardiac surgery in several centres. Such procedures have several advantages for the patient. The endoscopic
nature of the operation causes the patient significantly less pain, reduces the risk of bacterial infection, reduces the need for blood transfusions, and reduces the recovery time from over 7 days to 2 days. In addition, the ability to perform a second operation simultaneously means that the patient faces less operating time.

Despite all the advantages of robot-assisted surgery, there are some significant disadvantages, such as a limited field of view, reduced tactile feedback, and a diminished ability to respond to major complications.

First, in endoscopic surgeries, the surgeon has no “peripheral vision”, as he or she is restricted to the view provided by the robot-operated camera, and thus cannot have a sense of the situation immediately outside the camera’s field of view, unless the camera is moved. In addition, the camera limits the surgeon to a two-dimensional view of a three-dimensional operating field. Although this problem has not been solved, some advances have been made to improve the situation. In neurosurgery, a neuronavigating wand has been developed that provides a three-dimensional view of the brain from the point of view of the wand. The image is synthesized from previously captured tomographic images of the brain. However, this method itself has disadvantages, including the altered appearance of...

Figure 2. The da Vinci™ robot (Intuitive Surgical, Inc.) is one example of the type of robot used to perform complicated endoscopic surgery, such as cardiac surgery. Although it was not the system used in London, Ontario, it has been used elsewhere. (a) The surgical console used to control the robot from a distance. It contains foot pedals and translates the surgeon’s fingers onto miniature instruments. (b) The robotic arms. (c) The EndoWrist™ attempts to provide all degrees of freedom capable at the wrist. (d) A typical operating room incorporating a robotic setup. (e) The chest of a patient who has undergone beating-heart endoscopic CABG. In comparison, the classical approach involving a medial sternotomy would result in a much larger midline scar with greater potential for infection.
the brain on imaging a closed skull compared with the craniotomized skull. In addition, attempts have been made to give the surgeon a better three-dimensional picture using stereoscopic techniques (left and right eyes seeing slightly different images) and shadow optics (using two different light sources, and three-dimensional interpretation of the resulting shadows); these methods, however, are currently only in the experimental stage.10

When piloting a robot that operates on a patient, surgeons are not provided with the same tactile feedback that they would have if they were operating on the patient directly. Although this is of little clinical relevance in simple operations such as cholecystectomies, it severely limits the ability to perform more complicated procedures such as tumour excisions, as this often requires palpation of the tissue to determine the precise location and margins of the tumour.11 Prototypes designed to overcome this problem have focused on two principles: the feedback force of the tissue on the instrument, and the response of the tissue to vibration applied by the palpatiing instrument are measures that reflect the firmness and consistency of the tissue being palpated. However, this technology is still in its infancy; as it improves, the quality of the sensory feedback should also improve.

Lastly, as robots are automatons, their ability to respond to major surgical complications such as arterial bleeding is limited.9 Consequently, there would be a delay before the surgeon could respond sufficiently to rectify the problem. If the complication was serious enough, this could lead to increased morbidity. This obstacle, and the concern over robots that are not intrinsically safe have understandably slowed the introduction of robots into surgery.

Future Involvement of Robotics in Surgery
Robotic surgery is a rapidly advancing field that could be applied to several new areas. The ability to miniaturize technology has led to the field of microrobotics. Some current or potential uses of this technology include internal sensory devices, drug delivery systems, biopsy samplers, and artificial valves and sphincters. However, one of the most interesting areas where microrobotics is being explored is that of colonoscopy, where a microrobot could propel itself through the colon, documenting its journey along the way.12 A prototype that has shown promising results in vitro uses vacuum suction to adhere to and “walk” on the colonic wall, relaying information back to the endoscopist as it proceeds.15

A second area that is actively being examined is surgery in remote locations, an extension of the current limits of telesurgery. Already, robotic surgery is performed in a setup in which the surgeon is located several metres away from the patient, issuing commands to the robot that is operating on the patient. It is natural to try to extend this to performing surgery in more distant locations. However, several issues make its implementation difficult: the reliability of transmission lines, latency in transmission, and the ability to respond to complications. The latency in transmission time over remote distances restricts remote surgery to be performed over several hundred kilometres, and prevents data from being transmitted via satellites.3 One preliminary study that examined the effect of time delays on robotic surgical tasks showed that surgical accuracy decreased and the number of operator errors increased as the time delay in robotic response time and visual acquisition increased; a surgeon could only adequately compensate for a delay of less than 700 msec.15 Although transmission delay is an important problem, the inability of a robot to respond to complications is possibly the most important concern and is the most difficult to remedy, given the relative inflexibility of current surgical robots. As robotic technology advances, it is likely that robots will become more flexible in their movements and programming, and will be able to adaptively respond to complications as they arise.

Lastly, surgical education can be improved with the addition of robots to operating rooms. Currently, endoscopic surgery involves the surgeon looking at an image on a screen instead of at the real patient; it is thus plausible for the image to not be of an actual patient but of a virtual one, and for the surgeon to “operate” on this patient.3 In addition to a role in education, such simulated surgeries also have a role in preparing experienced surgeons for difficult and complicated operations.

Are Surgical Robots a Panacea?
As discussed earlier, robotic surgery can allow endoscopic surgery to be performed in new fields such as cardiac surgery, and this can lead to better patient outcomes, partly through faster recovery times. In these days of financial constraints, this is a desirable outcome as patients can leave the hospital earlier, resulting in substantial savings. It has been estimated that the cost savings could be as much as C$1,400 per day for an intensive-care bed.6 In addition, the use of robot-controlled laparoscopic cameras can free full-time staff to perform other tasks, thus saving on manpower costs as well. However, these savings come at a steep price, as the technology required to perform robot-assisted surgeries can cost up to $1 million (in the case of the Zeus™ and da Vinci™ systems) – money that might be better spent improving other aspects of patient care. A reasonable compromise might be to invest in technology that is compatible with the instruments and facilities already present at a hospital;14 the Toronto Hospital currently has plans to build several new operating theatres into which robotic surgical systems will be incorporated.15 However, it is important to remember that the movement towards technology should not be driven primarily by economics, but by patient outcomes.

Although surgical robotics is rapidly advancing, it is still a relatively new field that is untested on a large scale. In July, 2000, the FDA approved the first telesurgical robot, which involves the surgeon operating a console a few metres from the patient; the clinical trials on this robot involved 113 patients.10 Inevitably, other robots will also be approved by the FDA, and hospitals will need to address the issue of whether surgical robots are the most effective use of funds in terms of patient morbidity and mortality. In the free-market environment of the U.S., the centres that first espouse robotics will undoubtedly use it as a marketing tool to attract patients to their clinics, as they did over 10 years ago when laser treatment for coronary blockages showed promise.2 Just as it was later shown that this laser treatment was not beneficial, it is possible that robotic surgery may not benefit all patients. Well-designed, extensive trials are needed to determine who would benefit most from this technology, and whether the benefits of robotic surgery outweigh its costs.

Conclusion
Technology is becoming an increasing part of all facets of medicine, and surgery is no exception. Robotics is a rapidly expanding field that is revolutionizing the way surgery is performed. Its many potential advantages, including improved patient outcome, cost savings and educational utility make it an attractive area of development for those hospitals able to afford the large initial investment. However, cost savings and educational use are secondary con-
cerns when considering robotic surgery – improved patient outcomes should be the primary goal that drives the expansion of this field. To this end, more trials are required before the use of robotic surgery is deemed beneficial to patients and can be accepted by surgeons.

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References

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