Robotic assistance in microvascular surgery

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1. Introduction

The introduction of minimally invasive surgery in the early 1990s has rapidly changed the performance of surgical procedures in a wide range of surgical specialities. Postoperative pain, discomfort and morbidity are caused by trauma created by trying to gain access to the area of surgery, rather than by the surgical procedure itself. Through the application of minimally invasive surgery, several advantages are offered to the patient. Decreased post-operative pain, shorter hospitalisation, a more rapid return to work, improved cosmetics and reduced risk of wound infection and other post-operative complications are achieved by the performance of laparoscopy [1-5].

However, laparoscopic surgery also has it's limitations. The most important disadvantage is that only a two-dimensional image of the operating field can be provided, with a decreased depth perception as a result. Through experience, processing of monocular cues can be learned and depth perception improved. The adaptation of monocular cues, however, is a learning process through which performance times are significantly improved [6]. These adaptations are accounted for the increased mental fatigue and strain found with two-dimensional imaging. Other important limitations of laparoscopy are the limited manoeuvrability of effecter instruments, small working spaces, fixed angles at the trocar level to place sutures and the loss of direct contact with organs causing insufficient tactile information [1, 3, 6, 7]. Furthermore, the surgeon's tremor is amplified by the long instruments, which causes the use of laparoscopy in microsurgery to be problematic. Through all these limitations, a steep learning curve exists for the performance of laparoscopy [8].

Nowadays, minimally invasive surgery is widely applied in general surgery, gynaecology, urology and thoracic surgery. There is only little use of it in the divisions of plastic surgery, cardiothoracic surgery and vascular interventional surgery. Despite the technical advantages, laparoscopy is more difficult to be performed and more skills are required from a surgeon than with the performance of traditional surgery. The use of laparoscopy is especially problematic in microsurgery. A solution to all these problems can be provided by robotic surgery. Research has shown that robotic surgery is superior to traditional laparoscopy [8, 9]. By the participants of this study it was felt that robotic surgery was easier to learn than traditional laparoscopy. However, application of robotic surgery for the purpose of performing microsurgery is only in the first stage of development. This is unfortunate, while utilisation of robots in microsurgery offers the possibility to work really precise. An area where that feature is really important is the performance of microvascular surgery. Up to now, there has been only little experience with robotic surgery in this area.

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2. Why use robots?

Surgery is a technology driven profession. The development of robotic surgery was originally started for the possibility of tele-surgery. Surgical tele-manipulation is performing an operation through communication technology and robotics without being physically present at the operating table. This offers great possibilities for performing surgery on patients that are inaccessible. Inaccessibility could be due to several reasons: 1) unavailability of a surgeon (a surgeon in one hospital with particular expertise can assist a colleague in another institution or country), 2) the patient being in a hazardous environment (e.g. in case of a battlefield or a nuclear accident), 3) the patient presents a danger to the surgical team (radioactive contamination or contagious infection) or 4) the surgical team is a danger to the patient (e.g. an immunodeficient patient). The first operation where the surgeon was virtually present was performed in France by Professor Marescaux, where the surgical console was present in New York City and was connected to the three arms of the Zeus system in France [2]. This type of procedures would not have been possible without the advent of high-speed broadband internet technology to rapidly deliver the surgical commands from the console to the robot arms.

Today, robotic surgery is widely utilized in different medical professions, e.g. general surgery, gynaecology, urology, thoracic surgery and neurosurgery. The use of robotic surgery is mainly twofold. It is widely used for endoscopic procedures to perform minimally invasive surgery (MIS), while another area of utilization is the use of robots in microsurgery because robots offer the possibility to work really precise. The role of automation is to standardize a procedure. Surgical robots can reduce variations in patient outcome among surgeons and for an individual surgeon.

The use of robotic assistance has enabled humans to transcend their limitations by information gathering and sensing or by improved delivery on a microscale basis or in difficultly accessible areas [3]. Surgeons are allowed to perform tasks that currently require more than one person, dexterity is increased, a three-dimensional image is provided and the possibility to operate in very confined spaces is offered. A master-slave manipulator allows performance of superhuman tasks that would not be possible without computer enhancement [3]. These manipulators also regulate filtration of tremor and downscaling of robotic movements through removing all high-frequency oscillating motions and reducing all large movements into microscopic movements at the instrument tips. The only disadvantage of master-slave manipulators is that they make a system mechanically and electrically complicated from the perspectives of safety and maintenance [3].

3. Robotic systems

First-generation surgical robots consisted mainly of robotic arms that assisted the primary surgeon by holding and positioning instruments. Nowadays, surgical robots are the primary surgeon’s hands through a digital interface. Currently, two surgical telemanipulators are capable of performing remote telerobotic surgery: the da Vinci Robotic Surgical System (Intuitive Surgical, Mountain View, California, USA) and the Zeus Robotic Surgical System (Computer Motion, Goleta, California, USA). Surgical developed the da Vinci system at the urging of the Pentagon, in order to be able to perform remote operations without surgeons being at the front line or at sea [10]. With both systems, the surgeon is sitting at a console, the instruments appear right in front of his eyes and the controllers are in the same eye-

hand-target axis as found in open surgery, giving the impression that the instruments are an extension of the surgeon's hands [1].
Although there are many resemblances, there are also some technical differences between the two systems. With the da Vinci, surgeons are provided with a true 3D image obtained through binocular vision: different images are presented to each eye from a dual light source and dual cameras [2]. The 3D image on the Zeus system is achieved by viewing alternating 2D images on a monitor wearing special glasses. Manipulation systems are also different between the two systems. The da Vinci instruments are manipulated through friction-free devices held between forefinger and thumb, whilst Zeus instruments are manipulated by moving a ball-like hand interface. Both systems articulate at a "wrist" and offer seven degrees of freedom motion for the instruments. The master-slave can reduce tremor and downscale movements by 5:1 for the da Vinci and by 10:1 for the Zeus system. The advantage of the Zeus system is that, on the contrary of the da Vinci, it has three separate arms that provide the robot with a greater flexibility [2].
Both systems provide high visual magnification, movement scaling and tremor filtration, allowing for precise tissue dissection [11]. However, limitations in the current robotic systems are the lack of tactile feedback and potential interference between robotic arms [11]. A study of Sung and Gill showed that robotic laparoscopic procedures can be performed effectively using either the da Vinci or the Zeus system [11]. In this study, however, the learning curve and operating times were shorter and execution of the technical movements appeared inherently more intuitive for the da Vinci system [11].

4. Use of robotics in vascular surgery

Cardiac surgeons were the first to accept the application of robotic assistance in their surgery. Since robotic assisted technology became available, it has been successfully applied for aortic anastomoses in animal models. Surgical correction of aortic disease used to require a large incision in the abdomen and shifting of the abdominal viscera [12]. Through the use of robotic surgery the procedure has become minimally invasive, resulting in less post-operative pain and complications and improved cosmetics. Furthermore, robotic technology provides the vascular surgeon with the accuracy demanded to perform the delicate tissue handling necessary for aortic procedures.
From 1998 to 2000 Martinez et al. gained experience in using robotic surgery for performing aortic grafts in animal models [12]. In february 2001, Wisselink and collegues completed the first human aortic reconstruction using the Zeus system [12]. The procedure was performed in two patients. Since then, similar robotic surgery has been performed on many patients more. Research has confirmed the advantages of robotic use for aortic reconstruction. Kolvenbach and co-workers compared robotic versus manual aortic anastomosis times and found that times were shorter in the robotic group [12]. In addition, Stadler et al. found that the da Vinci robotic system facilitated the creation of the aortic anastomosis and shortened aortic clamp time in comparison to laparoscopic techniques [10].
Robotic surgery appears to be of most benefit in the area of microsurgery, while it can manipulate in a small space and finer and more controlled movements can be made without tremor. The use of robotics in microvascular surgery is the most recent area of development. And although not much experience has been gathered in this area, it holds great promises for the future…

5. Current experience in robotic microvascular surgery

Robot-assisted microvascular surgery was first introduced in cardiac surgery. Endoscopic instruments lacked the necessary degrees of angulation required and were insufficiently long to achieve a precise microvacular anastomosis in the chest [13]. In order for these problems to be solved, robotic surgery was introduced. In june 1998 Loulmet and colleagues performed the first clinical, totally endoscopic, computer-enhanced arrested heart coronary artery bypass in Paris [13]. A study performed on porcine hearts showed that a vascular anastomosis is easier performed by three-dimentional visualisation combined with robotic assistance than manually [13]. In 2000, the performance of arrested heart coronary artery bypass surgery was repeated with the Zeus system by Reichenspurner and his team in Munich [13]. The first report of coronary revascularization on a beating heart was in 2001 [2]. Using both the Zeus and the da Vinci System, over 2000 coronary bypass procedures were performed by the first half of 2002 [1]. From 2002 to 2004 robotic assisted TECAB surgery was performed on 98 patients divided over 12 centres [14].This study demonstrated that it is safe and efficient to perform this operation in patients by robotic means.

Except for the use of robotics in cardiac surgery, robots are still rarely used in microvascular surgery. Especially the area of reconstructive microsurgery demands optimal visualization, technical skill, precise surgical manipulations and minimization of tremor. All these demands are well sufficed by robotic surgery. Experienced microsurgeons operate at an accuracy of 50 µm; robotic assistance refines this accuracy by a factor of 10, to 5 µm [4]. Although high free-flap success rates are achieved by microsurgeons, the loss of a free flap is a dramatic event for the patient. Mostly, a compromised free flap is the result of a technical error. The frequency of these technical errors may be reduced by the use of robotic surgery. Several studies on this subject are already performed.

Already in 2000 the Robot Assisted MicroSurgery (RAMS) was used to perform vascular anastomoses of the rat femoral artery, both in vitro and in vivo. The RAMS system proved to be applicable in microsurgery, with the advantages of greater precision and more rapid manipulation compared to the surgeon [15]. Remarkable was that macro movements take more time accomplished by the robot than by the surgeon, while micro maneuvers are performed equally fast or even more rapid by the RAMS system than by the surgeon. Thus, when a surgical procedure approaches the micro level, the time difference between the surgeon and the robotic system is equilibrated.

In 2001 Le Roux and colleagues also used the RAMS system (NASA's Jet Propulsion Laboratory, Pasadena, CA and MicroDexterity Systems Inc., Memphis, TN) to anastomose carotid arteries in rats [16]. All vessels were patent and the error rate was similar to that of conventional techniques. However, using the RAMS system was associated with a significant increase in operating time, particularly due to an increase in time required for needle positioning and knot tying [16]. This increase in operative time may reflect a learning curve. The RAMS system improved the performance of medical students and engineers doing the same task and that of plastic residents carrying out a variety of microsurgical procedures [16].

Karamanoukian et al. used the Computer Motion Zeus Robotic Surgical System to anastomose 1-mm arterial vessels harvested from explanted pig hearts. They concluded that the Zeus robotic technology had certain advantages over the conventional human assistant, with the major advantage being the ability of scaling down the surgeon's movements to a microscopic level [17]. Another experiment of their group showed an important conclusion.

It proved that robotically assisted microanastomoses can be mastered equally well by surgical trainees and fully trained vascular surgeons [18]. Prior experience with open microsurgical procedures does not facilitate use of the robotic system. This conclusion may have important consequences for the future of microsurgery. Nowadays, only few surgeons share the experience to perform microsurgery. However, when robotic assistance would be used, microsurgery can be performed equally well by all surgeons and residents. This way, microsurgery can be applied amply in the medical world. Furthermore, anastomosis times were significantly longer using the robot compared to traditional freehand technique for the residents as well as for the fully trained surgeons.

In addition, research on performing end-to-end anastomoses in rat femoral arteries with Zeus showed that the Zeus system is effective at performing complex, open, microsurgery tasks in vivo, although there was no measurable benefit from robot-enhanced surgery [19]. A remarkable degree of tremor filtration was observed by the surgeon in the robot-enhanced cases as well as the feeling of exerting a greater precision when placing sutures. Anastomoses done by hand were significantly faster than those done with Zeus. This, however, could be a result of the large instruments available for Zeus. While they are three to five times larger than microsurgical instruments, it is more difficult to perform microsurgery with them [19]. This could also have contributed to the outcome of another experiment where vascular anastomoses were performed using the Zeus system on prosthetic conduits in a laparoscopic training box [20]. Although vascular anastomoses could be made with equal quality compared to manual procedures, robotic assistance resulted in significant longer suture and knot tying time, more failings during the procedures and more actions needed to perform the procedure. These problems may decrease when working with robotic instruments that are suitable for microsurgery.

In 2005 the first experimental microvascular surgery was performed in a pig using the da Vinci Surgical system. The robot was used to perform vessel adventitiectomy and microanastomoses. In performing a free flap the robotic assistance offered numerous advantages: elimination of tremor, scalable movements, fully articulating instruments with six degrees of spatial freedom and a dynamic three-dimensional visualization system. Despite the advantages, drawbacks were also present, with the absence of true microsurgical instruments being the most important one [21]. Preparation of the robot, including draping and positioning the arms, was performed in 27 minutes. The time to perform the microsurgical procedures (adventiectomy, arterial and venous anastomosis) took 44 minutes.

Recently, our department has gathered the first clinical experience in reconstructive robotic microvascular surgery when we performed a microvascular anastomosis in a muscle sparing free TRAM-flap. Using the da Vinci Surgical System (Intuitive Surgical, Inc, Sunnyvale, US) the arterial adventectomy and anastomosis was performed using 9/0 nylon sutures. The time to perform this anastomosis was about 40 minutes, which is significantly longer than the standard technique (around 20 minutes). To put a sterile draping around the robot took 20 minutes, but did not increase operating time while it was performed during dissection of the flap. Conclusions from this experiment are that the advantages of robotic surgery were not yet translated into a clear advantage, e.g. decreased operating time, however that can be achieved with more experience [22]. Again, the increase in operating time is partially due to the fact that this robot is not suited for the performance of microvascular surgery.

In 2006 a group of plastic and cardiothoracic surgeons used the Aesop robotic arm (Computer Motion Inc, Santa Barbara, CA, USA) to harvest internal mammary vessels for breast reconstruction in 20 patients [23]. The vessels were brought out through a passage in the second intercostal space. However, there is no need for such a complex procedure, while removing cartilage from the third or fourth rib provides a vessel long enough to perform an anastomosis. Their study also revealed a high incidence of complications. Although the study of Boyd et al. did not show convincing advantages, it should be further investigated whether there could be a role for robotic surgery in harvesting internal mammary vessels in breast reconstruction.

6. Advantages of robotic assistance in microvascular surgery

Normally, the full potential of microsurgery is limited by the manual dexterity of the individual surgeon. The physical and intellectual possibilities of surgeons differ. On top of that, the microscope magnifies and exaggerates all movements while it limits visual field and depth. Microsurgery requires that the surgeon spends long hours in a relatively fixed posture, which can be really tiring and can adversely affect the surgeon's technical performance. Finally, the microsurgical instruments act as extensions of the surgeon's hands and magnify physiological tremor [16]. In order to perform microsurgery optimal visualisation, technical skills, precise surgical manipulations and minimalization of tremor are important. These aspects are better sufficed by a robot than a surgeon. Advantages obtained by use of robotic assistance are a three-dimensional view, greater three-dimensional precision, better access to difficult areas, a larger range of motion, down scaling of movements to tissue level, tempering of incorrect movements or tremor, consistent reproducibility of movements and improved ergonomics [4, 6, 16-20, 24-26]. Furthermore, robots are not subjected to fear, stress or fatigue. Through all these advantages robotic surgery can potentially diminish tissue damage.

Prasad et al. compared the accuracy of robotic assistance without motion scaling to robotic assistance with the addition of motion scaling in a trial. There was a significant improvement in accuracy of 20-30 % for the groups with motion scaling [4]. This indicates that motion scaling is mainly responsible for the improvement in accuracy when using robotic assistance. A smaller role in accuracy seems to be assigned to tremor filtration [4]. Motion scaling also has the possibility to reduce operating time and to equalize the performance of the dominant and non-dominant hand [4].

Three-dimensional vision offers the advantage of improved depth perception and accuracy. A study showed that novice and advanced surgeons performing anastomotic drills with the da Vinci robot, were both 65 % faster and more accurate when working in three dimensions than in two [8]. Prior robotic experience was not necessary to benefit from 3D viewing [8]. Another study using the da Vinci robotic system showed that drill performance times were significantly reduced by using 3-dimensional vision when compared to 2-dimensional vision [6]. Error rates were also significantly improved by using 3-dimentional vision. The subjective impression of surgeons experienced in working with 2D and 3D view was that in performing anastomoses on a pig heart 3D-visualization improved coordination between the right and left instrument [25]. This facilitated handling of the needle. Especially transfer of the needle from one instrument to the other was easier, which reduced the forces applied to the needle and suture.

Research has shown that no transfer of training exists in performing microvascular anastomoses with robotic assistance for it requires totally different skills. This implies that when robots are developed for performing microvascular anastomoses, this procedure can also be carried out in peripheral hospitals instead of only in microsurgical centres, which is the case nowadays. This will be an extreme booster for the application and development of microvascular surgery.

The development of robotic systems to assist surgeons in performing microsurgery is a growing field of research. Robotic surgery holds promises for an evolutionary future. Expectations are that with more experience microvascular anastomoses can be performed more rapidly and with greater precision when using robotic assistance.

7. Problems concerning robotic microvascular surgery

Robots provide excellent opportunities for the future of microvascular surgery. However, at this point of time no robots have been adjusted for performing microvascular surgery. The current robots exhibit some problems. First of all there is no software designed for handling blood vessels, restricting the robot’s range of motion and performing microvascular anastomoses. Furthermore, robots cannot operate with true microsurgical instruments what makes it difficult to manipulate the blood vessels effectively. In addition, their needle holders are too large to place a microsurgical suture [19, 21]. Another possible point of improvement is the creation of the anastomosis. Sutures need to be performed by multiple persons, while the use of small metal clips (nitinol clips) can decrease anastomosis time [27]. This possibility should be further examined in the near future.

The most discussed problem is the lack of haptic feedback [3, 15, 24]. Surgeons have to rely on visual cues to estimate the forces that they exert on the tissue. This is often a cause of broken sutures and torn delicate tissues, resulting in prolonged operative times and possible injury to the patient [24]. On the other hand, there are also surgeons that do not experience the lack of haptic feedback as an important issue. According to them, traditional microsurgery does not rely on haptic feedback, as before a microsurgeon can feel the small forces when a needle tears through a 1-mm vessel, the surgeon should see the vessel being stretched. This is found to be similar when using the robot [21]. Research has indeed shown that the lack of haptic feedback is partially compensated by visually observing deformation of the tissue [24]. Several studies have been done investigating the effect of haptic feedback. From all these studies it was concluded that haptic/ force feedback lowered suture tension and the amount of tension applied was significantly more consistent than without feedback [24, 28]. The force magnitudes applied with any force-feedback method more closely approximate the manual suture tension than forces applied without feedback [28]. Forces achieved with sensory –substitution modes did not vary significantly from the manual forces achieved with hand ties [28]. The consistency of these robot-assisted ties is equivalent or superior to those attained with hand ties [28]. Conclusively, sensory feedback improves the consistency of robotically applied forces [28]. Furthermore, research has shown that visual feedback systems were not as effective as vibrotactile feedback systems [28].

A huge drawback is the cost of a robot: it ranges from $ 750,000 to $ 1 million [11, 15, 21]. And also the maintenance costs should be considered. On top of that, the application of robotic surgery requires specially trained personnel and a dedicated surgical team. However, in the long run, these costs can be covered through the advantages of robotic surgery, e.g. by working more efficient more patients can be operated on in a shorter period

of time and with less assistance, and hospitalization will be shortened because of the decreased complication rate.
Some ethical issues have been raised concerning the use of robotic surgery. It is questioned who takes responsibility for harm caused by robotic surgery and when it is ethically appropriate for robots to be used? These questions can only be answered satisfactionally when experience in robotic surgery has been gathered.
However, the advantages of minimally invasive surgery justify the development of robotic surgery. Reducing robotic drawbacks should expand the use of robotic surgery. Thorough research needs to be performed in order to optimalize the use of robotic systems in surgery. For that to happen, a less conservative surgical community and an adapting industry are needed.

8. Does a learning curve exist in robotic surgery?

Many studies have demonstrated that there is a learning curve for robotic-assisted surgery [4]. Although a learning curve exists, it can be methodically overcome [1, 26]. The role of the mentor is critical in the process to overcome the challenges and flatten the learning curve [26]. Research has shown that educational experience of the fellow revealed improved operative times [26]. Mean robotic setup time, mean total robotic operative time and mean total operative time were all significantly improved when more experience was gathered [26].
In a study where surgeons performed a synthetic small bowel anastomosis in a closed box simulator, performance significantly increased between the first and the last task and also operative time was significantly reduced [1]. The number of movements also significantly reduced between the first and the last task and appeared to be a useful tool to measure performance [1]. A research performed on patients executing coronary bypass surgery on the beating heart indicated that there is a significant moderately steep learning curve, which is mitigated by further experience [29]. In CABG anastomoses on the beating heart, there existed a learning curve during the first 18 to 20 patients [29]. From the first to the last quintile there was a significant 40 % decrease in operating time [29]. Another study in which anastomoses were performed with the Zeus system showed that in the early cases, the surgeon broke sutures and bent the needles frequently [19]. After this learning period, these were both rare events.
Another remarkable finding was done. No significant difference in performance or time was measured between experienced and nonexperienced surgeons performing synthetic small bowel anastomoses [1, 9]. In another study where surgeons performed an anastomosis on a pig heart using the Zeus telemanipulator system, novice and experienced surgeons showed quite similar learning curves and anastomosis times [25]. This indicates that there is no transfer of traditional microsurgical skills to robotic microsurgical skills.
From all these studies it can be concluded that a learning curve indeed exists for the performance of robotic surgery. However, it is demonstrated from different studies that the learning curve for robotic-assisted surgery is actually shorter compared to that of traditional laparoscopic surgery [9, 18]. In combination with all the other advantages that robotic surgery holds over laparoscopic surgery, it can be concluded that the use of robotic assistance in microvascular surgery in time will definitely be worth wile.

9. Future expectations

Because robotic surgery offers great possibilities for the future of microvascular surgery, more and more surgeons and technicians will gather their strengths to improve the current technology and create robots that are perfectly suited to assist surgeons in the performance of microvascular surgery. Developments will probably focus on designing robots specialized in open procedures, creating software for the handling of blood vessels and performing microvascular anastomoses, adjusting needle holders to safely place microsurgical sutures and developing a haptic feedback system for the surgeon. These developments may have important impact on the future of supermicrosurgery, which is defined as anastomosis of blood vessels 0.5-0.8 mm in diameter [30, 31].

It is expected that robots will be designed that are specialized in microvascular surgery. This brings surgeons the opportunity to perform microvascular anastomoses more precisely and more successfully. With more experience microvascular anastomoses are expected to be performed more rapidly than in the conventional way. Because no transfer of training exists, microvascular surgery can also be performed in small hospitals, which will be an extreme booster for the application and development of microvascular surgery.

Robotic technology has the potential to mutinously increase patient safety in surgery in the next decades. Further clinical trials are needed to explore the clinical potential of robot-assisted microvascular procedures.

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The first generation of surgical robots are already being installed in a number of operating rooms around the world. Robotics is being introduced to medicine because it allows for unprecedented control and precision of surgical instruments in minimally invasive procedures. So far, robots have been used to position an endoscope, perform gallbladder surgery and correct gastroesophogeal reflux and heartburn. The ultimate goal of the robotic surgery field is to design a robot that can be used to perform closed-chest, beating-heart surgery. The use of robotics in surgery will expand over the next decades without any doubt. Minimally Invasive Surgery (MIS) is a revolutionary approach in surgery. In MIS, the operation is performed with instruments and viewing equipment inserted into the body through small incisions created by the surgeon, in contrast to open surgery with large incisions. This minimizes surgical trauma and damage to healthy tissue, resulting in shorter patient recovery time. The aim of this book is to provide an overview of the state-of-art, to present new ideas, original results and practical experiences in this expanding area. Nevertheless, many chapters in the book concern advanced research on this growing area. The book provides critical analysis of clinical trials, assessment of the benefits and risks of the application of these technologies. This book is certainly a small sample of the research activity on Medical Robotics going on around the globe as you read it, but it surely covers a good deal of what has been done in the field recently, and as such it works as a valuable source for researchers interested in the involved subjects, whether they are currently “medical roboticists” or not.

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