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REVIEW ARTICLE

Technical review of the da Vinci surgical telemanipulator

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Abstract

Background The da Vinci robotic surgical telemanipulator has been utilized in several surgical specialties for varied procedures, and the users' experiences have been widely published. To date, no detailed system technical analyses have been performed.

Methods A detailed review was performed of all publications and patents about the technical aspects of the da Vinci robotic system.

Results Published technical literature on the da Vinci system highlight strengths and weaknesses of the robot design. While the system facilitates complex surgical operations and has a low malfunction rate, the lack of haptic (especially tactile) feedback and collisions between the robotic arms remain the major limitations of the system. Accurate, preplanned positioning of access ports is essential.

Conclusion Knowledge of the technical aspects of the da Vinci robot is important for optimal use. We confirmed the excellent system functionality and ease of use for surgeons without an engineering background. Research and development of the surgical robot has been predominant in the literature. Future trends address robot miniaturization and intelligent control design. Copyright © 2012 John Wiley & Sons, Ltd.

Keywords da Vinci; surgical robotics; laparoscopy

Introduction

The development of the da Vinci surgical telemanipulator was initiated by SRI International, an independent non-profit research institute, as a research project funded by the US Army. The aim of this project was to develop a system by which surgeons could operate on injured soldiers from a remote secure location. The assessment of the first prototype system indicated the true potential of the system: 'to provide a technical solution to the intrinsic limitations of manual laparoscopic surgery' (1), which, despite its advantages, impose significant restrictions to surgeons (2) (Table 1). These technical restrictions could be overcome by articulating and controlling the tips of instruments, thereby improving the range of motion and dexterity. Intuitive Surgical is a company that was established in order to modify the telemanipulator to a format compatible for use in minimal access surgery. In 1995, Intuitive Surgical acquired the rights to SRI patents, and has begun working on the telerobotic system (1).The first version of the da Vinci system had no instrument-specific arm. In 2003, Intuitive Surgical introduced a significant upgrade to the system by offering a fourth instrument arm, dedicated to the camera–telescope

Table 1. Limitations and adverse effects of manual laparoscopy

Limitation	Adverse effect
Two-dimensional (2D) vision from a conventional monitor	Reduces perception of depth
Poor eye–hand coordination	Decreases ergonomics and dexterity
Instrument guidance	Requires ambidextrous manual activity
Long rigid instruments	Magnify the surgeon's natural hand tremor
Instruments have only five degrees of freedom (DOFs): four for positioning of the tip and one for the actuation	Limit the surgeon's natural range of motion, decreasing dexterity
Fixed abdominal entry points	Limit the workspace reachable with the instrument's tip
Instrument tip and handle move in opposite directions	Technical drawback known as the fulcrum effect, which decreases the motor perception capability
Camera instability	Contributes to surgeon fatigue
Limited tactile feedback	Reduces dexterity

assembly. In 2006, the S version introduced high-definition imaging and the Tile Pro multi-image display. This particular feature provides the surgeon with additional information from auxiliary video signals (e.g. vital signs and CT or ultrasound images). Furthermore, the system provides a greater work space via instrument extension and increased range of movement.

The latest generation, the da Vinci *Si* System, was released in April 2009 and has a dual console that allows two surgeons to work collaboratively. This allows more efficient training of residents and surgeons, especially those unfamiliar with robotic-assisted surgery. The *Si* version also has several improvements, which enhance the surgeon's control of the operative field and the operating room (enhanced vision, refined master controllers, simplified control footswitch panel and further ergonomic settings).

To date, there have not been any detailed technical analyses of the da Vinci robotic surgical telemanipulator, although it has been referenced in several publications and is used routinely. The objective of this work was to review the technological features of the da Vinci telemanipulator, highlighting technical limitations, advantages, and future trends in surgical robotic research and development. In this review, publications on basic and all other versions of the da Vinci Robotic system are included.

Methods

Published studies on technological features of the da Vinci telemanipulator were obtained using the PubMed and ISI Web electronic databases (http://www.ncbi.nlm.nih.gov/pubmed, http://apps.isiknowledge.com). The search was restricted to *English language* studies. Design details of patents filed by Intuitive Surgical and other publications not indexed on ISI Web or PubMed databases were included in the information gathering and analysis process. Relevant papers were required to address the technological aspects of the da Vinci robotic system throughout various specialties.

Results

We found more than one thousand publications in the literature concerning the robot, from which we selected those related to technical aspects.

The results are divided in four sections. The 'da Vinci design' section details the mechanical design, control design and main features (i.e. 3D vision and robot workspace). 'Advantages offered by the robot' detail stereoscopic vision, proficiency and learning curves. 'Limitations of the robot' include malfunctions and other drawbacks, such as lack of haptic feedback. A section on ongoing research used to enhance system performance is also included.

da Vinci design and system description

The da Vinci teleoperated robotic system is based on a master–slave control concept. It consists of two major units. The surgeon's console unit houses the display system, the surgeon's user interface and the electronic controller. The second unit consists of four slave manipulators, three for telemanipulation of surgical instruments and one dedicated to the endoscopic camera.

The da Vinci system provides the surgeon with an immersive operating environment with high-quality stereo visualization and a man–machine interface that directly connects the movement of the hand of the surgeon to instrument tip movement inside the patient. The surgeon visualizes stereoscopic images via a 3D display above the hands, restoring hand–eye coordination and providing intuitive correspondence with manipulations. Furthermore, the controller transforms the spatial motion of the instruments into the camera reference frame, i.e. the surgeon has the virtual sensation of operating within the patient's body. Finally, the da Vinci system restores degrees of freedom (DOFs) lost in conventional laparoscopy; the three-DOF wrist inside the patient allows natural wrist pronation/supination, providing a total of seven DOFs for instrument tip control (three orientations, three translations and grip). The da Vinci control system filters out surgeon tremor, making the instrument tips steadier compared to traditional laparoscopic instruments. Furthermore, the system allows variable motion scaling from master to slave (3).

From a functional viewpoint, the system offers two features: visualization of the surgical field with the endoscope connected to the 3D display, and transformation of the surgeon's hand movement to that of the surgical instruments.

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The patient sidecart (Figure 1) consists of a moveable base with four mounted arms: one for the endoscope and three for instrument manipulation. The arms are attached to a central column by means of vertical prismatic joints. Each arm has a set of 'non-actuated' joints, which position the distal part of the kinematic chain containing active joints. The passive joints are manually adjusted by releasing the relative brakes. The active joints can be manually adjusted or controlled by the surgeon by means of the master interfaces (4). A complete kinematic diagram of a tool arm is shown in Figure 2.

The DOFs θ_{11}, θ_{12}, are integrated in the sterilizable surgical instruments realizing the articulated tip (Figure 3). The roll around the instrument shaft is represented by θ_{10}. An additional DOF is integrated in instruments such as scissors and graspers for opening and closing.

The da Vinci surgical instruments are hooked on a rail that allows insertion and extraction in and out of the patient's body (P_9). The passive joints indicated with bold dots in Figure 2 form a double parallelogram (Figure 4) that creates a remote centre of motion (RCM). This kinematic structure determines a fulcrum point distally located from the structure itself. Typically, this fulcrum point is at the skin entry point. This allows correct orientation of the robotic instrument without changing position to the entry point, thus avoiding tissue damage.

The robot moves the pitch of the instrument's shaft by moving the entire arm, supporting the rail actuating the parallelogram (θ_8). The more recent versions of the robot implement this mechanism without the parallelogram but with preservation of the same functionality. The joint θ_7 moves the jaws of the instrument's shaft, rotating the entire remote centre of motion mechanism. The other joints (passive or servo-assisted) are manually moved at the beginning of the intervention to adjust the position of the arms and the fulcrum point. During the intervention they are usually locked.

The surgeon controls the slave sitting on a stool by the console, which is positioned remotely from the patient (Figure 5). The console serves as an interface between surgeon and robot. The surgeon views the operation through binoculars within the console hood. If the surgeon removes his/her head (detected by an infrared beam) from the binoculars, the robotic arms are deactivated.

The surgeon's arms are supported by padded armrests. The surgeon can adjust specific functions of the vision system [height of binocular system; two-/three-dimensional

Figure 1. Da Vinci Si HD patient side cart (http://www.intuitive-surgical.com)

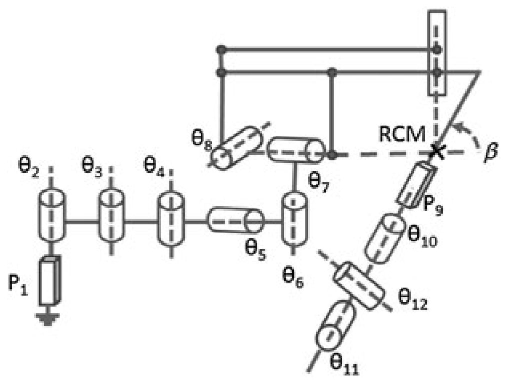

Figure 2. Kinematic configuration of each da Vinci arm consisting of a mechanical chain of links and joints. The symbol, on the left, represents the floor of the room where the cart is positioned. Prismatic joints (P_i) represent links that can translate with respect to the previous one. Rotary joints (θ_i) represent links that can rotate with respect to the previous one. The rotary angle (β) represents the remote centre of motion (RCM) fixed with the entry point on patient skin (terminology adopted from (4))

Figure 3. Detail of a microsurgical Endowrist™ instrument (http://www.intuitivesurgical.com)

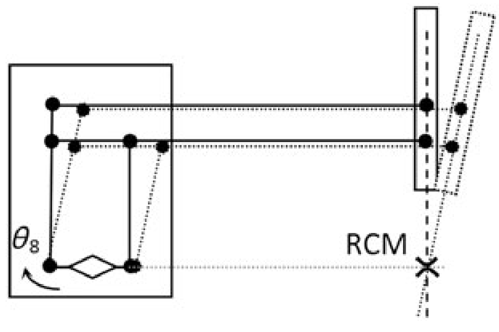

Figure 4. Double parallelogram forming the RCM. Actuation of θ_8 joint moves the instrument shaft around RCM (terminology adopted from (4))

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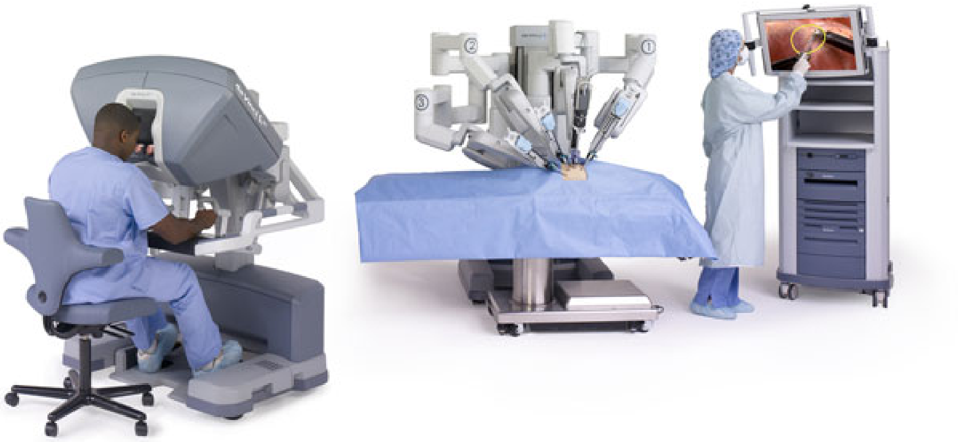

Figure 5. The surgeon at the console and the patient side cart of the da Vinci Si HD Surgical System (http://www.intuitivesurgical.com)

(2D/3D) switch; 0°/30° viewing endoscope selection] and the robotic arms (motion scaling between master and slave) with a panel of buttons on the armrests. The surgeon can control other system functions with five foot pedals, including the selection of the two active slave manipulators (1) by means of two master interfaces (right and left) located in the console, consisting of two kinematics chains. The same master interfaces are used together to control camera positioning.

Figure 6 shows the da Vinci handle. The thumb and index finger of each hand are placed in a gripper interface, attached to each handle of the distal part of the master interface, by means of adjustable Velcro straps. The surgeon's fingers are virtually connected to the jaws of the instrument tip.

Each handle allows rotations around the three Cartesian axes of a reference frame fixed on the handle (Figure 7). Each handle has a redundant joint (No. 4) which allows the finger gripper to have the largest range of orientation (US Patent No. 6364888B1).

Each handle is attached to the proximal part of the master interface, which has three additional DOFs and is used to translate the end-effector (Figure 8).

Figure 6. The da Vinci handle used to remotely move the instrument's tip

Mapping movements of the master interfaces with the slaves manipulators

The controller registers the movement of the surgeon's hand to the motion of the end effectors (instrument tips). The system restores hand–eye coordination, projecting the endoscope image above the surgeon's hands by means

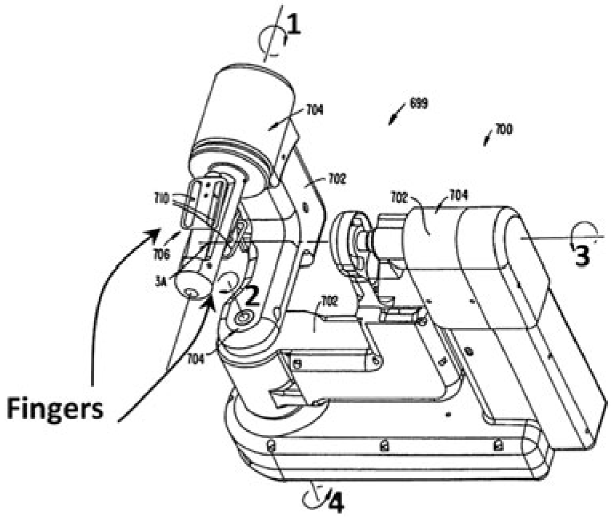

Figure 7. Design details of the da Vinci handle (US Patent No. 6364888B1). The virtual gripper interface, moved by the fingers, allows rotation of the four sensorized joints shown in the figure

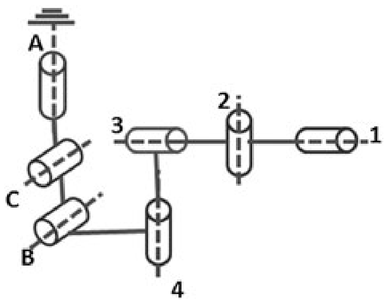

Figure 8. The da Vinci master interface

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of mirrored overlay optics to provide motion correspondence (5). In this way the surgeon is virtually immersed in the patient's body.

The angles between the virtual gripper interface frame and the display frame are repeated by the controller on the slave, between the end effector and camera frames (Figure 9). The end effector frame origin is placed on the fulcrum of the real surgical gripper, since the virtual gripper interface frame origin is positioned on the fulcrum itself. In this way each rotation around the virtual gripper interface fulcrum is reproduced around the real gripper fulcrum (Figure 9).

The three DOFs of the proximal part of the master interface are used to translate the end-effector. Additionally, the translations are referred with the camera reference frame. Relative translations between the virtual gripper interface and the display frame are repeated by the controller on the slave, between the end effector reference frame and the camera reference frame. Thus, if the surgeon moves the virtual gripper interface by 1 cm to the left with respect to the display, using motion scaling 1:1, the surgical instrument gripper fulcrum moves to the left with respect to the camera frame by 1 cm, and so on.

Translations are mapped as relative, while rotations are mapped as absolute movements. The use of relative motion control allows a comfortable zero position for the surgeon's arms. The surgeon, when utilizing the clutch foot pedal, activates a friction functionality, which uncouples the master from the slave manipulator so that the master can be repositioned in the centre of the workspace for better ergonomics (1). The repositioning of master interfaces is possible only on translational DOFs. For example, if during the repositioning the surgeon also moves the orientation, the system indicates the need to let go the master grippers and then automatically restores coherent orientation to the slave end-effectors. Thus, the master console uses motors that are deployed to reposition the master interfaces whenever needed. With regard to camera position for optimal viewing, camera movement control is performed using the two master interfaces together.

Immersive stereoscopic viewing

The da Vinci console provides immersive stereoscopic viewing. The surgeon, inserting his/her head into the hood, obtains a stereoscopic view of the operating field through the binoculars. The console hood serves to block peripheral vision, providing a fully immersive experience.

The da Vinci stereoscopic visualization system is composed of a 3D endoscope with two separate optic channels, connected to a pair of charge-coupled device (CCD) chip cameras. The optic channels have a distance of 6 mm between axes, resulting in retinal disparity (different image in each retina), which thereby creates a true stereoscopic image. This image considerably helps surgeons in orientation and manipulation in complex operative landscapes (1). Images after noise filtering are displayed through high-resolution monitors, mounted in front of the eyes and providing a stereoscopic view (6).

Robot workspace: importance of optimal port placement

Optimal positioning of the robot and trocar sites is essential for maximizing performance of the robotic surgical procedure. Their positioning influences robot dexterity and reach of the surgical field. Trejos *et al.* (4) used the global conditioning index (GCI) to optimize port placement in cardiac surgery (4). CGI is an index that measures robot dexterity within the entire workspace.

There are other factors that must be considered in port site selection, such as the minimization or avoidance of collisions between robot arms, obstacles around the patient and the patient him/herself. One study used an *in vitro* model, consisting of cubes in the size range 40–150 mm, which evaluated the surgeon's ability to perform tasks in different spaces using the da Vinci surgical system (7). This study involved seven participants, who performed five drillings in seven cubes. The study confirmed that when the workspace is large, maintaining

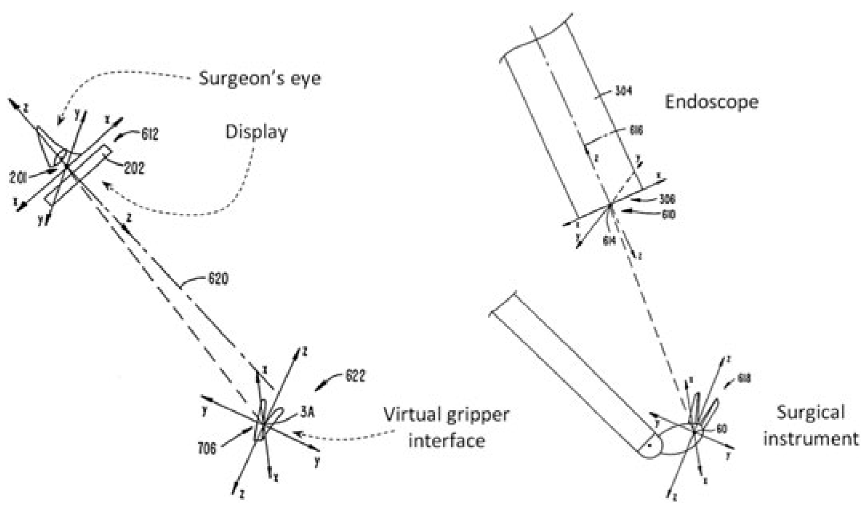

Figure 9. Relation between the eyes of the surgeon with respect to his/her fingers (A) and between the endoscope and the instrument tip (B) (US Patent No. 6364888B1)

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an adequate distance between ports helps to avoid external collisions between robot arms. In situations of restricted workspace, the distance between ports is reduced (50–60 mm), making execution difficult; for small workspaces (40–45 mm) it is impossible, due to collisions of the arms. This can be explained by analysing the design of the slave arms. The workspace encompassed by a single robot arm is large (many of the joints can be rotated 360°) and intra-arm collisions are limited because of the arm's design. However, the workspace becomes limited with simultaneous use of two (or three) arms, due to collisions. In addition to collision between instrument shafts (as with manual laparoscopic surgery), there is the additional risk of external inter-arm collision. In particular, rotation of the entire remote centre of the motion mechanism (supporting the instrument rail) can produce collisions. With closely positioned access ports (4–5 cm) when the target field is deep, the external parts of the arms can come to lie almost parallel to one another, increasing the risk of collision. Some authors state that optimal port placement is only acquired with experience (8,9).

Advantages offered by the robot

Despite the benefits of the minimally invasive approach, laparoscopic and thoracoscopic surgery impose major ergonomic restrictions on the surgeon, which increases the difficulty in execution of major abdominal and thoracic operations. Additionally, the manual laparoscopic approach increases surgeon discomfort, due to the awkward stance and fatigue during long operations. Robot-assisted laparoscopic technology was developed as a solution to overcome these limitations; much research has been done to evaluate the effectiveness of the robotic surgical system with respect to manual laparoscopic surgery. The most widely reported advantages of the da Vinci robotic surgery stem from wristed instrument motions with seven DOFs, scaling for precise movements, elimination of hand tremor, stereoscopic vision and improved ergonomics. A further advantage of the da Vinci system is the ability to eliminate innate handedness, based on results obtained by surgeons performing tasks with both dominant and non-dominant hands (comparable performance with either hand) (10).

2D, 3D and stereoscopic viewing

The video image plays a crucial role in laparoscopic procedures due to the loss of tactile and force feedback, since it is the only interface between the surgeon and the operative field. In manual laparoscopy, the surgeon operates from a 2D screen, with consequent lack of depth perception (11), whereas the da Vinci robotic system allows a natural stereoscopic view with more depth cues, enabling more accurate and efficient endoscopic manipulations (12). Early studies investigating the benefits of 3D over 2D vision reported contradictory results. In fact, some studies show better motor performance with 3D vision, while others not (13). It should be noted that all reported comparative studies used first-generation, non-stereoscopic 3D systems with lower resolution, and eye-shuttering technologies (LCD or polarizing glasses) not used in the da Vinci system. The da Vinci system provides immersive stereoscopic vision based on true retinal disparity.

Munz *et al*. (6) reported a study which confirmed that performance with stereoscopic imaging by the da Vinci system was significantly better than that of 2D. The study recruited 11 surgeons with minimal experience in robotic surgery, who performed four tasks, which included the most common movements used in robotic-assisted surgery. The study was randomized and blinded, based upon imaging mode (2D or stereoscopic vision). The results demonstrated that the stereoscopic mode reduced execution time for every task by one-third and improved dexterity by 25%, as measured by the reduction of the number of movements and distance travelled. Accuracy, based on error reduction rate, improved by nearly 100%.

Other studies have reported that only complex tasks are performed more easily and quickly with stereoscopic vision, with no difference between the two imaging modalities for simple tasks (14,15). However, one study showed that stereoscopic vision allowed for significant improvement in execution time and error rates for both inexperienced residents and advanced laparoscopic surgeons (5). Blavier *et al*. (12) evaluated the impact of 2D and stereoscopic viewing on task efficiency (execution time) during a surgical task. In this study, 60 inexperienced subjects and 20 expert surgeons performed a standardized surgical task using the da Vinci robotic system. All participants were separated into two groups, one using stereoscopic and the other using 2D viewing. The results showed reduced execution time with stereoscopic imaging compared to 2D viewing for inexpert subjects, while performance with the two imaging modes was similar for expert surgeons. Interestingly, all subjects correctly estimated their time performance with 2D viewing, whereas all overestimated real execution time when using stereoscopic imaging, indicating that 2D and stereoscopic images are processed and memorized differently. The results of this study confirmed the importance of stereoscopic viewing in improving performance, and underlined the subjective estimation of task efficiency. In a recent laboratory-based study, Silvestri *et al*. (16) compared 2D, binocular 3D and 3D autosteroscopic displays. The auto-stereoscopic display provided results comparable with binocular 3D, but necessitated more training. Surgeons involved in the study preferred the use of the 3D binocular system.

Performance and learning (proficiency) curve

Publications on performance, training and proficiency with the da Vinci system date back to 2003. One of the

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first reports tested the comparative efficacy of robot-assisted vs manual laparoscopy utilized standardized tasks of increased level of difficulty common to minimally invasive training programmes (17). Sarle *et al*.(18), in an *in vitro* laboratory study, demonstrated that inexpert surgeons performed all tasks more quickly and with greater precision with the robot than with conventional laparoscopy. This difference was significantly more marked for more difficult tasks, confirming the da Vinci system's usefulness for interventions in which fine movements and optical magnification was necessary (17–20). Others reported accelerated proficiency gain by inexpert surgeons with robotic-assisted surgery, as compared with manual laparoscopy, demonstrating that basic skills are acquired more rapidly with the robot (21–23). Only one author found evidence to the contrary, reporting faster training with manual laparoscopy (20).

Kaul *et al*. (23) reported prior experience in open or laparoscopic surgery not to be essential for the acquisition of competence in robotic procedures, although this conclusion lacks weight because of small sample size. Di Lorenzo *et al*. (19) reported reduced execution time by experienced laparoscopic surgeons. Obek *et al*. (24) evaluated skill transfer ratios between manual and robotic laparoscopy and concluded, despite skills transfer with either technique, that training with manual laparoscopy is superior to training with robots only (24). Jacobs *et al*. (21) evaluated the impact of haptic feedback on robotic surgery training; they implemented a telemanipulator system with two master interfaces, one for the trainer and one for the trainee. The trainee's interface was not controlled by the trainee but followed the movement of the trainer in the haptic interface. The study, which involved inexpert surgeons, was divided in two groups: traditional visual training and haptic–visual training; the latter group showed enhanced skills acquisition.

Other studies have attempted to identify objective variables to distinguish skilled and unskilled performances and define the proficiency–gain curve, which confirms the acquisition of the necessary skill level for safe robotic surgery with the da Vinci telemanipulator (21,25–31). These authors used the application programming interface (API) by Intuitive Surgical to acquire real-time data from the da Vinci system, e.g. position of instruments, velocities and trajectories. Verner *et al*. (30) examined robot proficiency and concluded that it would be possible to discriminate between expert and inexpert operators by analysis of the trajectories. Hernandez *et al*. (29) used objective structured assessment of surgical skills and motion analysis, including task completion time, path length and the number of movements performed, to assess surgical skills and determine proficiency. Judkins *et al*. (26) proposed the use of electromiographic signals indicative of muscle fatigue to assess proficiency, and demonstrated reduction in muscle fatigue with training. In a subsequent study, the same authors (27) trained medical students by providing real-time feedback of their performance during the exercises and reported that real-time grip force feedback enhances training. They demonstrated that provision of grip force feedback (not available in the real robot) reduced the applied forces during subsequent performance of the same tasks with the real robot.

Limitations of the robot

System malfunctions and robustness

The system malfunctions are well documented in the literature, especially in relation to failures during urological surgery. Table 2 summarizes the malfunctions published in the literature. A recent survey by Kaushik *et al*. (32) documented the retrospective experience of 176 surgeons; 56.8% of the surgeons reported an irremediable intraoperative malfunction; 80 mechanical failures occurred before starting robotic-assisted radical prostatectomy, of which 57.5% (46 cases) were rescheduled, 18.8% (15 cases) were converted to open surgery, 15% (12 cases) were converted to conventional laparoscopic prostatectomy and 5% (4 cases) were completed by docking another robot; 63 mechanical failures were experienced before starting the urethrovesical anastomosis, of which 41.2% (26 cases) were converted to open surgery and 31.7% (20 cases) to standard laparoscopy; 15.8% (10 cases) were completed with one less arm, and in 4.7% (three cases) the operations were aborted; 32 malfunctions were reported before completion of the anastomosis,

Table 2. Malfunctions of the da Vinci robot reported in the literature

Studies on the number of malfunctions for groups of interventions	Type of intervention	No. of cases	Total amount of malfunctions	Conversion rate due to malfunctions
Nayyar and Gupta, 2009	Urology	340	37 (10.9%)	2 (0.6%)
Borden *et al*., 2007	RLRP	350	9 (2.5%)	3 (0.9%)
Lavary *et al*., 2008	RALP	8240	34 (0.4%)	10 (0.1%)
Kim *et al*., 2009				
	General, gynaecological, thoracic, cardiac and otorhinolaryngological surgery	1797	43 (2.4%)	3 (0.2%)
Study on the retrospective experience of surgeons	Type of intervention	No. of surgeons	Surgeons with malfunctions experience	
Kaushik *et al*., 2010	Urology	176	100	

RLRP, robot-assisted laparoscopic radical prostatectomy; RALP, robot-assisted laparoscopic prostatectomy.

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of which 62.5% (20 cases) were converted to standard laparoscopy and 37.5% (12 cases) to open surgery. The nature of the component malfunction was never mentioned in this study, and was based entirely on the retrospective experience of surgeons, rather than on the actual number of cases, giving no indication of the failure rate of the da Vinci robot in urological surgery cases.

Nayyar and Gupta (33) reported critical mechanical failures which resulted in a conversion rate of 0.6% in a retrospective study of 340 cases, comprising a total of 37 incidents during surgery (10.9%). These authors emphasize the importance of a complete preliminary check to ensure proper functioning of every component of the robot before the induction of anaesthesia, since malfunctions can be recognized before surgery. Borden reported a similar failure rate: 2.6% (nine cases) of 350 robotic-assisted laparoscopic radical prostatectomies (RLRP) could not be completed robotically, due to system malfunction (34). Six malfunctions were detected prior to induction of anaesthesia, and the intervention was rescheduled. Malfunctions were due to: set-up joint malfunction ($n = 2$); arm malfunction ($n = 2$); power error ($n = 1$); monocular monitor loss ($n = 1$); camera malfunction ($n = 1$); breaking of surgeon's console hand piece ($n = 1$); and software incompatibility ($n = 1$). Three malfunctions occurred intraoperatively (0.86%) and were converted to either conventional laparoscopy (one case) or open surgery (two cases). No details of the nature of the robot failures were provided in this report.

Two similar studies, with larger case series, report a lower critical malfunction rate during the intervention. Lavary (2008) reported the results of a questionnaire regarding the number of equipment used during robotic-assisted laparoscopic prostatectomy (RALP), the number of procedures that were converted or aborted and the component that malfunctioned. Eleven institutions with a median number of 700 surgeons participated, for a total of 8240 cases. Critical failure occurred in 0.4% (34 cases) with abortion (24 cases) and conversion (10 cases) to laparoscopy in two and to open surgery in eight cases. The main sources of malfunction were the optical system and arms, but it is not clear which component malfunction determined conversion (35).

In a single-institution study, Kim *et al.* (36) reported insurmountable malfunctions during interventions in general surgery, obstetrics and gynaecology surgery, thoracic and cardiac surgery and otorhinolaryngology surgery. Malfunctions occurred during surgery in 2.4% of the cases (43 of 1797). The report did not provide clear details on the number of malfunctions that determined the cancellation of the intervention; it simply reported that malfunctions determined conversion in 0.17% (three cases). During radical prostatectomy, open surgery conversion was performed due to a malfunction of the master arm. Two laparoscopic conversions were performed, one during radical prostatectomy (due to wire cutting of the master interface) and one during gastrectomy (ill-defined malfunction of the robotic arm).

Many recoverable mechanical problems during surgery are related to robotic instrument malfunction, including broken tension wires or wire dislodgement from the working pulleys, non-recognition of the instrument by the robot (despite available residual use) and a locked instrument. However, these errors can be corrected or bypassed (albeit with additional operating room time). The incidence of critical failures due to technical problems requiring conversion was very low compared with the conversions reported during manual laparoscopic operations, which are reported to reach up to 16% for some major procedures (37). This low rate of technical problems is probably the consequence of system characteristics: robust mechanical mechanisms and the use of traditional and established technology for building links, joints and power transmission (except those of the surgical instruments).

Lack of haptic feedback

Lack of haptic feedback is a major unresolved problem, as the da Vinci surgical telemanipulator does not offer any kind of haptic feedback. This is particularly relevant during the execution of complex tasks (27). The two important adverse consequences of this lack of haptic feedback during robotic surgery are the inability for surgeons to identify tissue consistency, enabling discrimination between tumour and normal tissue (38), and the execution of intracorporeal suturing and knot tying, especially with fine suture material (39–41), with frequent breakage of the suture.

Ongoing research

Research work done in last 10 years has been directed to overcome existing deficiencies of robotic surgery, e.g. haptic feedback, enhancement of system integration and the combination of augmented reality navigation functionalities. Other research and development activities aim to realize outstanding training systems, including the next generation of virtual reality simulators.

The addition of haptic (force and tactile) feedback has been identified as an essential requirement for improved performance of robotic surgical systems. Culjat *et al.* (42) demonstrated that, during grasping, surgeons apply less force using tactile feedback. They designed a tactile feedback system on the da Vinci system that allowed surgeons to perceive digital pressure; the system was evaluated by experiments involving four subjects, who were required to grasp a pressure-sensitive phantom, with and without tactile feedback. However, Akinbiyi *et al.* (43) indicated that, in view of the current limitations in sensing and control technologies, direct haptic feedback implementing to the surgeon's hands for clinical application remains a challenge. They proposed an augmented reality system to provide force input (sensor substitution) to the da Vinci system. Force sensors (strain gauges) were mounted in Wheatstone bridge configuration on the

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robotic instruments. The feedback provides real-time graphic representation of the force (two circles, one for each instrument, that change colour according to force used and based upon three force levels). The visual representation of the force level is overlaid on the streaming video acquired from the camera. The system has been tested by several users in a phantom knot-tying task. The authors concluded that all subjects found task execution easier with the augmented reality system; furthermore, the system decreased suture breakage. Herrell *et al*. (44) demonstrated the benefit gained from augmentation of laparoscopic images with preoperative images; additional image guidance to the da Vinci robot has the potential for improved performance, including excessive removal of benign tissue. Kenngott *et al*. (45) developed an experimental navigation system that provided real-time information on the position and orientation of the working instrument in relationship to the tumour. Voruganti *et al*. (46) reported an augmented reality navigation system and tested it on an electronic phantom. The system generated a 3D reconstructed model of the coronary arteries from preoperative angiographic images. After registration of the model to the patient, the 3D model of the coronary artery tree was placed as an overlay on the video frames acquired from the endoscopic camera.

Some researchers have integrated other imaging technologies in the da Vinci system. For example, Leven *et al*. (47) integrated a laparoscopic ultrasound probe with the da Vinci system (da Vinci Canvas). The ultrasound image was displayed as a picture-in-picture, or directly overlaid on the endoscopic image in the position with respect to the ultrasound probe. As the laparoscopic ultrasound probe is placed in front of the endoscopic camera, this technology allows viewing of the ultrasound image as though it was virtually attached to the probe. The authors used the system during liver cancer surgery, where intraoperative ultrasonography (IOUS) is widely used. The authors stress the versatility of the system, which can be useful for several other procedures. Other researchers (48) have reported on the design of new robotic instruments, including a pulse-modulating device, the robotic Gyrus PK (RG-PK), manufactured specifically for the da Vinci system in 2008.

Other studies have focused on surgical simulation and training. Coste-Manier *et al*. (49) presented 'Simulation and Training Architecture for Robotic Surgery (STARS)', an integrated system based on augmented reality in all activities of robotic intervention: planning, simulation and execution. An animal experiment was performed, highlighting difficulties with time limitation and logistics, and the necessity of increasing intraoperative precision and organ movement during tracking techniques used with augmented reality. Sun *et al*. (50) developed a user-friendly computer-based simulator for the da Vinci robot. They used two modified Phantom Omni (SensAble Technologies) to simulate the handles of the da Vinci console, such that all instrument controls completely reproduced da Vinci kinematics. The system also includes a feature to evaluate workspace reach, fixing robot position and skin entry points. The authors concluded that the system had the potential to be a promising tool for training and planning operations. One group (51) developed a telesurgery simulation training system for use with the da Vinci robot, a soft tissue model based on the patient's anatomy and a master console using two Phantom Omni interfaces (SensAble Technologies). With this simulator, the surgeon could perform manipulations similar to those performed by forceps on the real da Vinci. Kenney *et al*. (52) developed the dV-Trainer, a virtual reality simulator for the da Vinci Surgical system commercialized by Mimic Technologies. Other available commercial virtual reality surgical simulators are: RoSS (Simulated Surgical System), SEP Robot (Sim Surgery), and the da Vinci Skills Simulator (Intuitive Surgical System).The latter system was developed in collaboration between Intuitive Surgical Science and Mimic Technologies and is integrated directly into the da Vinci console.

From a mechanical viewpoint, ongoing research and development should focus on the development of robotics for single-port surgery and the use of teleoperated fully implantable mini-robots to reduce the invasiveness and size of existing robots. The SPRINT robot (Araknes EU F7, European Consortium) is an example of a novel robotic platform for single-port laparoscopic surgery (SPLS) and has a master–slave configuration not dissimilar to that of the da Vinci robot, with a bimanual solution (53–55). Other groups (56–58) have demonstrated the feasibility of small fully implantable robots, asserting that implantable robots can be manipulated from the outside with much less force and trauma to the tissues, allowing for better precision and delicate tissue handling.The feasibility of implantable robots has been demonstrated; however, these devices are still developmental and are tested only in animal models. Further research and development is required to refine current design concepts into clinical translation.

Discussion

This review has analysed the da Vinci surgical telemanipulator from a technical viewpoint. The da Vinci system creates an immersive operating environment for the surgeon by providing both high-quality stereo-visualization and a man–machine interface that directly connects the surgeon's hands to the motion of the surgical instrument tips inside the patient's body. The surgeon visualizes the operative field by a stereoscopic display located above the hands, restoring hand–eye coordination and providing intuitive correspondence with manipulations. The system restores degrees of freedom lost in conventional laparoscopy by placing a three-DOFs wrist at the functional end of the instrument, enabling natural wrist pronation and supination, and providing a total of seven DOFs for control of the instrument tips. The system is also able to abolish surgeon tremor and enables variable motion scaling.

Several studies have confirmed the robustness of the da Vinci system, with a reported critical mechanical failure

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rate requiring conversion or alternative operative strategy of 0.4–0.6%. Many of these mechanical failures can be identified by a complete check of the robot before induction of anaesthesia. Reported malfunctions include set-up joint malfunction, arm malfunction, power error, monocular monitor loss, camera malfunction, mental fatigue, breaking of the surgeon's console handpiece and software incompatibility.

Lack of haptic (especially tactile) feedback is a major unresolved problem of the da Vinci surgical telemanipulator, and is particularly relevant during the execution of complex tasks, such as intracorporeal suturing and knot tying, especially with fine suture material. Optimal positioning of the robot and port sites is crucial to the expeditious performance of robotic surgery. Port positioning must minimize collision between the external arms, instruments and camera in both the operating field and the operating room. Although the workspace reachable by a single robot arm is large, it is considerably reduced due to collisions when using two (or three) arms simultaneously.

Current trends in the development of new surgical robots must address the improvements offered by the da Vinci telemanipulator. In particular, all robotic platforms for laparoscopy, single-port laparoscopic surgery (SPLS) and natural orifice translumenal endoscopic surgery (NOTES) propose a da Vinci-like man–machine interface that directly connects the surgeon's hands to the motion of the surgical instrument tips, in conjunction with stereoscopic visualization, motion scaling and tremor filtering. The solutions proposed to date improve mechanics and develop smaller robots, which are sometimes totally intracorporeal, inserted through a single port, thereby completely avoiding collision between external robot arms. All the improvements we have reviewed concern teleoperated systems, where the surgeon, from the master console, commands the robot (slave) to exactly replicate his/her movements. Research on robotic surgery should produce new intelligent control designs, not based only on master–slave paradigms. The most innovative future improvements will include the development of smart robots that will assist the surgeon in an active way, i.e. by means of optimal use of information contained in radiological images, developing robots that 'know the anatomy' and can prevent possible surgeon errors.

Conclusion

This review has outlined the current state of the art of the technological aspects of the da Vinci manipulator, in an attempt to better define system design, its deficiencies and its strengths. The review confirms the robustness, excellent functionality and advanced features of the da Vinci robot, including high-quality stereoscopic imaging, all of which contribute to its ability to facilitate the execution of complex advanced laparoscopic procedures by reducing difficulty and thereby improving task quality. The robustness of the system is confirmed by the low rate of system malfunctions. Its current limitations include lack of haptic (especially tactile) feedback, and collisions between robot arms and other obstacles, which require accurate port positioning. Our review therefore identifies the areas where progress in technology is needed, and highlights the research performed to improve the system. Despite its limitations, there is a substantial body of evidence confirming the utility and benefit of the da Vinci system; this aspect has not been addressed in depth, as it falls out of the scope of this review. This review also provides a detailed account of the advances in training systems for robotic-assisted surgery, for both residents and established surgeons who wish to adopt robotic surgery in their practice.

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