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Robotics In Vivo: A Perspective on Human–Robot Interaction in Surgical Robotics

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human–robot interaction, surgical robotics, automation, robot autonomy, user interface

Abstract

This article reviews recent work on surgical robots that have been used or tested in vivo, focusing on aspects related to human–robot interaction. We present the general design requirements that should be considered when developing such robots, including the clinical requirements and the technologies needed to satisfy them. We also discuss the human aspects related to the design of these robots, considering the challenges facing surgeons when using robots in the operating room, and the safety issues of such systems. We then survey recent work in seven different surgical settings: urology and gynecology, orthopedic surgery, cardiac surgery, head and neck surgery, neurosurgery, radiotherapy, and bronchoscopy. We conclude with the open problems and recommendations on how to move forward in this research area.

1. INTRODUCTION AND SCOPE

Robots have been used in vivo since the 1980s. Unlike robots in other industries, surgical robots must be held to the same standard as other medical devices. The effectiveness of the intended procedure and the safety of both users and patients are paramount in these systems, which must be validated thoroughly before being used in vivo. One of the biggest factors in ensuring safety and effectiveness is the interaction between the user (typically a surgeon) and the robotic system.

The first recorded use of robotics in the operating room was in 1983 in Vancouver, British Columbia, Canada, where a robot called Arthrobot (1) was used as a limb-positioning assistant during orthopedic procedures. Using voice commands, the surgeon could ask the robot to move the patient's lower limb in a range of positions. Other preliminary works in surgical robotics involved modifications to industrial robots from companies such as Unimation (Danbury, Connecticut, USA). In 1985, a Programmable Universal Machine for Assembly (PUMA) 200 robot was used to position a stereotactic frame to guide a brain biopsy probe under the guidance of computed tomography (CT) (2). Similarly, in the late 1980s, a PUMA 560 with six degrees of freedom (DOFs) was modified with an attachment with two additional DOFs to perform transurethral resection of the prostate (3). Trials on patients raised concerns of safety, guiding future iterations toward purpose-built systems (4–6).

The development of clinical robotic systems accelerated in the 1990s. First used in 1992, ROBODOC was an autonomous robotic milling system designed to help perform total knee arthroplasties (7). Despite thousands of patient cases in Europe, the US Food and Drug Administration (FDA) did not approve the device until 2008 (8). The first robot approved by the FDA was the Automated Endoscopic System for Optical Positioning (AESOP) robot developed in 1994 by Computer Motion (Goleta, California, USA) in collaboration with NASA (9, 10). Surgeons could use voice commands to have this robot position an endoscope during laparoscopic surgery. Further development led to the release of the ZEUS robotic surgical system, which added two additional arms that precisely mimicked the surgeon's movements to manipulate tissues in the surgical field of view. Around the same time, the da Vinci system (Intuitive Surgical, Sunnyvale, California, USA) was being developed. The two systems received FDA approval in 2001 and 2000, respectively. Computer Motion and Intuitive Surgical merged in 2003, and as a result, the ZEUS system was phased out in favor of the da Vinci, which became the only commercially available surgical robot at the time (11). Since then, many robotic systems have been developed for a wide range of surgical applications (11–13).

What is common to all surgical robotic systems is the goal of overcoming limitations of traditional techniques or enhancing the capabilities of surgeons. This goal can be accomplished by, for example, mitigating hand tremors through the user's manipulators, enhancing visualization of anatomical structures with registered medical images, or even performing complete surgical tasks through supervised autonomy using a simple interface.

In this article, we focus on how robotic systems in vivo manage the human–robot interaction and how these interactions are taken into consideration to improve the user experience in the operating room. Most previous research efforts have focused on improving teleoperative systems (14). As most of the major issues in this area have reached sufficient levels of maturity, we focus more on recent efforts that have improved human–robot interaction in multiple applications of robot-assisted surgery, and we review the design requirements for developing surgical robotic systems from the perspective of human–robot interaction. We consider only surgical systems that have been used or tested in vivo. We conclude the article by pointing out the open problems in this area, with an outlook for where we think this exciting area is heading in the future.

2. GENERAL HUMAN–ROBOT INTERACTION REQUIREMENTS FOR SURGICAL ROBOTS

Regardless of the application area, there are several design requirements that should be met for successful physical human–robot interaction in the operating room. In this interaction, the humans include patients, surgeons, and their surgical teams. An important goal in human–robot interaction design in surgery is to overcome the main challenges faced by surgeons.

2.1. Surgical Robotics Challenges Faced by Surgeons

The design of effective human–robot interactions in surgery should address the typical challenges that surgeons face in most surgical procedures. Broadly speaking, these challenges fall into three categories (15): decision-making at each step of the surgery, navigation inside the human body, and object recognition (see **Figure 1**).

The first challenge, decision-making, refers to the process of deciding on the best next step for the patient at each stage of the surgery. Systems that help in decision-making are of great importance, and this is one aspect of human–robot interaction in surgery (16). For example, imaging modalities such as ultrasound can provide more information to the surgeon, with the hope that this information will help in making the right decision. Another possibility is to build autonomous systems that can make decisions on their own, as in the case of autonomous surgical robots (17). Shared-control robotic systems (18), in which the surgeon and the robot make decisions cooperatively, can also be used.

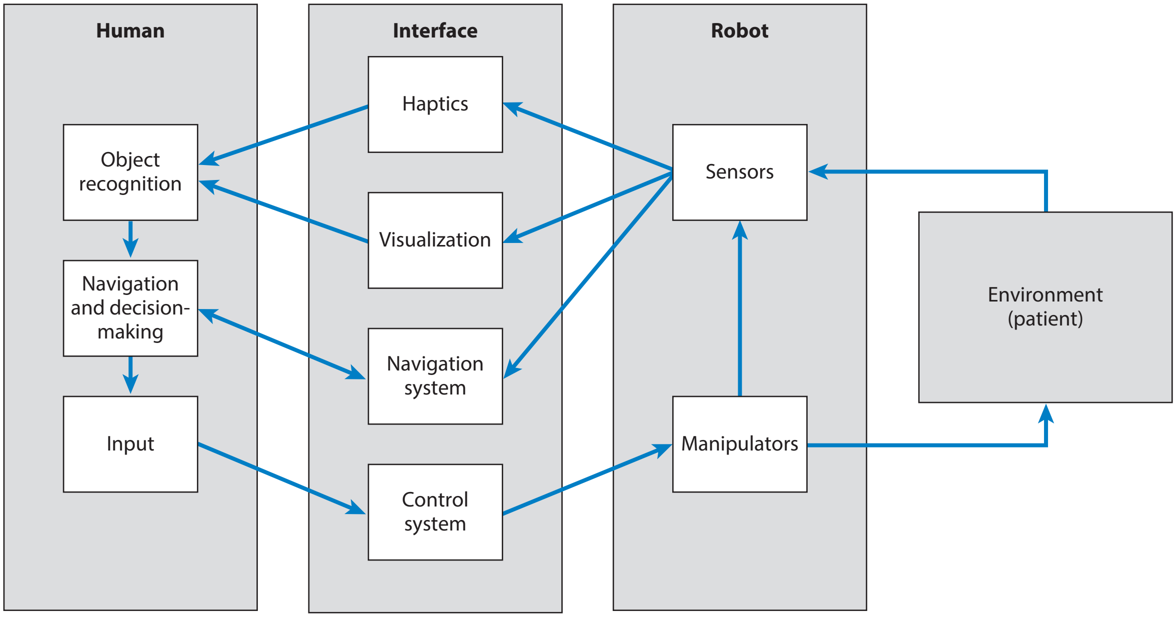

Figure 1

Overview of human–robot interaction components in robot-assisted surgery and how they relate to the major challenges faced by surgeons. The surgeon's input is passed to the robot using a control system, which moves the robot's manipulators to interact with the patient's body. The robot's sensors (such as force and vision sensors) send feedback signals to the surgeon through the different interface components (such as haptics and visualization). These signals are used by the surgeon for decision-making, navigation, and object recognition.

The second challenge, navigation, refers to moving from one location to another inside the human body without risking harm to tissue. In some cases, navigation can be done autonomously (17, 19). Guidance systems, such as those employing augmented reality, can guide the next move of the surgeon during the procedure (20). Automated path planning is another example of helping surgeons navigate safely inside the human body (21).

The final challenge is object recognition—that is, recognizing tissues and/or organs throughout the stages of surgery. In open surgery, surgeons use a mix of haptic and visual feedback, in addition to their knowledge of the anatomy, to help them in this process. With the lack of haptic feedback in many available robotic systems, this problem may become more challenging, especially for novice and intermediate surgeons. This challenge also appears in deciding which surgical plan to work on. To overcome these challenges, haptic feedback in robot-assisted surgery has been studied extensively (22, 23). Object recognition systems can also be helpful in improving the surgeon's situational awareness (24).

2.2. Clinical Requirements

Clinical requirements span several dimensions, including operating time, system complexity, and cost. One of the main clinical requirements in any surgery is to reduce operating time as much as feasibly possible. Researchers have studied the operating times of robot-assisted surgery compared with other types of surgery (e.g., conventional laparoscopy) and have found that the use of robots in surgery is often associated with longer operating times (25, 26). Among the reasons for the longer times is the lack of haptic feedback, which can then require surgeons to spend more time identifying and manipulating tissues based only on visual feedback (27). The robot's docking/setup time and instrument changes also contribute to delays (28). Therefore, it is important to reduce the complexity of the docking process and to use robotic systems with a small operating room footprint in order to streamline setup. Additionally, it is important to demonstrate that the high costs associated with robot-assisted surgery are justified by its benefits compared with other types of surgery. This topic is still under debate (29, 30).

Data integration is another important consideration in designing effective human–robot interactions inside the operating room. Data integration refers to allowing surgeons access to the data they need during surgery to help them make correct decisions. The data could, for example, include images of the patient from multiple imaging modalities, such as ultrasound, CT, and magnetic resonance imaging (MRI). One example is the work of Li et al. (31), which allows surgeons to control ultrasound machines from the da Vinci surgical console; another is work aimed at developing MRI-compatible robots (32). Augmented reality can be used in this context to overlay useful information on the surgical console (33). The data integration aspect can also be useful for surgical training; for example, data recorded from experts using surgical robots can be used to improve the motor skills of novice surgeons (34, 35) as well as for the objective assessment of surgical skills (36).

2.3. Technological Requirements

Many technologies can be employed to satisfy these clinical requirements. Moreover, new technologies also have the potential to enable new surgical procedures or techniques that are not otherwise feasible. These technologies help make the surgical platform, tools, visualization, and control systems suitable for procedures while considering the ergonomic aspects for all members of the surgical team.

Surgical platforms should preferably be small in size and weight, which will meet the clinical requirement of using platforms that have a small operating room footprint. Small platforms are also easier and faster to set up before the operation. Furthermore, designers should ensure that surgical platforms are stable enough throughout the different stages of the procedure (27).

The surgical tools should be as flexible and dexterous as possible, which is especially important in scarless or single-port surgery. Increasing the number of DOFs of the surgical tools can help achieve this goal. Flexible and articulated continuum robots (37) can be used. Using wireless modules to control the tools can also provide better dexterity than wired controllers. Furthermore, the design of surgical tools should allow the surgeon to reach any point in the surgical workspace (38) and should allow the exertion of sufficient force at the tool tip to manipulate the target tissue. Because surgeons often need to change instruments during the procedure, the tool design should facilitate this exchange in a quick and easy manner to save time during surgery (39). The movement resolution for the surgical tools should meet the requirements for each type of surgery, and motion-scaling methods are often used in commercially available systems to help achieve this goal (40). All of the above aspects are especially important in natural orifice transluminal endoscopic surgery (NOTES), in which the tools are inserted through one of the natural orifices inside the body, and many robotic systems have been proposed to address these requirements in NOTES (41, 42). There is, however, no clinical platform for NOTES that satisfies all of the above considerations, and this has presented a major barrier for the wide adoption of this type of surgery (43).

Visualization systems are crucial for any surgery. Many systems use stereoscopic visualization to give a 3-D view of the surgical scene, often using a single endoscope. Some problems still exist, however, such as occlusions (44) and a lack of depth perception (45). The use of multiple endoscopes can solve some of these problems (46). It is important for such systems to maintain visual–motor alignment to facilitate the control of the tools (47).

The control paradigms used in surgical robots span the entire spectrum from full teleoperation to full autonomy (48). Full teleoperation, which gives the surgeon full control over the robot, is by far the most widely used control method in commercially available surgical robots (49). In another method, called shared control, the final action of the system is the summation of the surgeon's and robot's inputs (50–53). A third method, traded control, decomposes the task into some parts that are executed fully by the human and other parts that are executed fully autonomously by the robot (54, 55). Next comes supervisory control or autonomy, in which the surgeon gives high-level commands to the robot, and the robot executes the task autonomously; in this case, the surgeon can still intervene at any time during the task execution to update or modify the robot's execution plan (56, 57). Finally, the most ambitious of the control methods is full autonomy, in which the robot executes the task autonomously and the surgeon does not intervene at all (58–63).

2.4. Human Aspects

When considering human aspects in robot-assisted surgery, we refer primarily to three main actors: the patient, the surgeon, and the surgical team. It is important to consider the requirements related to each actor in the design of surgical robots and to note that some of the requirements for one actor may conflict with the requirements of the others. This highlights the need to make trade-offs based on the available resources subject to maintaining the patient's safety and improving surgical outcomes.

Human aspects have played an important role in improving surgical practice throughout the development of medical robotics and will continue to be important for the future advancement of the field. For example, the transition from conventional laparoscopy to robot-assisted surgery was motivated partly by the goal of providing better ergonomics for the surgeon during the procedure by removing the fulcrum effect and providing better visualization. From the regulatory perspective, in 2016 the FDA updated its guidance document on applying human factors to medical devices to require usability testing to assess the impact of high-risk tasks on patients and/or other users (64).

In this context, Aaltonen & Wahlström (15) studied the views of a group of surgeons on some of the ongoing research in surgical robotics to get their perspective on which technologies would be most beneficial for their practice. The authors presented several technological developments to the group, such as haptic feedback (65), eye tracking (66), voice control (67), and augmented reality (68), and the surgeons considered technologies involving the use of the robot's display and video to have huge potential in overcoming challenges in the user experience. Such technologies include, for example, methods for adding landmarks to the display to facilitate the navigation inside the human body (15). The surgeons also highlighted the need for more extensive investigation of other human-related aspects, such as trust, safety, security, and ergonomics.

In a similar vein, Catchpole et al. (69) compared robot-assisted surgeries with traditional non-robotic techniques from a human factors perspective. They found that robot-assisted surgery affects the communication between the surgical team members, which leads to the need for new training methods. The reason of this disruption in communication is that, in many surgical robotic systems, the surgeon is sitting away from the rest of his or her team, mostly looking exclusively at a surgical console. Furthermore, the authors argued that the introduction of surgical robots shifts the workload during surgery, increasing it for some members of the surgical team while decreasing it for others (mainly the surgeon).

The decision-making process during robot-assisted surgery has also been studied. For example, Wahlström et al. (70) studied how surgeons adapt to the demands of several situations during surgery. The authors studied and analyzed real surgeries and videos of real surgeries along with comments from surgeons on their own practice during these surgeries. They concluded that the ability to adapt in response to sources of uncertainty is important during the various phases of robotic surgery. For example, during prostate surgery, uncertainties in where nerves critical for urinary function are located may affect the surgeon's decision-making, requiring potential adaptations in their workflow. Interfaces should therefore be designed to reduce the level of uncertainty, which in turn facilitates the decision-making process during surgery. Randell et al. (71) interviewed medical personnel who are experienced in robotic surgery and learned about issues of decision-making from their perspective. They found that the relationship between the surgeon and the rest of the team is very important because the team can provide more information that supports the surgeon's decision-making process, including details on the state of the patient and robot and details on areas that are not in the surgeon's field of view. A high level of trust and communication enables surgeons to focus more on the console and improves their overall concentration.

2.5. Safety Considerations

Safety is of paramount importance in surgical robot design. Satisfying the stringent requirements of government bodies for systems to be approved for use in vivo requires many cycles of development along with extensive documentation regarding design, testing, and manufacturing. Safety must also be considered in the design of the system itself. Hardware and software redundancies are needed to ensure that a single point of failure does not result in harm to the patient or user (14). Redundant position encoders, for example, can be used as consistency checks to monitor potential failures. If a failure does occur, systems can employ a fail-safe architecture, where the failure causes the robot to enter a safe state (e.g., going limp or completely freezing manipulator motion). Another architecture is fault tolerance, where the system continues normal functionality despite a failure (72). A fail-safe architecture is sufficient in most medical robotic systems, as holding robotic arms still in the event of failure does not increase the risk of injury to the patient or surgeon.

Another consideration is how much error is allowed in the system before safety concerns arise. Systems designed to be used in ophthalmic procedures, for example, must have tighter tolerances than general surgery robots. To mitigate errors, feedback controllers in each joint must be implemented with low error and latency (72).

To ensure patient safety during normal operation of the robot, the risk of inadvertent excessive force to tissues must be mitigated. Ficuciello et al. (73) outlined impedance control schemes that allow for a high degree of compliance between robotic manipulators to reduce interaction forces during physical human collaborations or when a tool collision occurs. In a similar vein, in the case of minimally invasive surgery, the risk of injury to the access ports on the patient's body must be minimized. These robots often have a remote center of motion to constrain manipulator motion such that it is stationary at the point of entry. Aghakhani et al. (74) described a control scheme with visual task-based evaluation of a laparoscopic camera arm with a remote center of motion.

In a human–robot interaction context, the robot must also be designed such that the interaction maintains or enhances patient safety. Intuitive sensory information to the surgeon can help determine context intraoperatively, such as haptic feedback through virtual fixtures (75) or improved surgical field visualization using 3-D cameras, as with the da Vinci endoscope. Systems can also ensure safety by preventing robot motion or action when the surgeon is not fully engaged in the interaction. For example, with the da Vinci surgical system, if the surgeon does not have his or her head in the surgeon's console, the manipulators freeze until attention is given back to the robot.

3. AREA-SPECIFIC HUMAN–ROBOT INTERACTION

One of the design decisions for surgical robots is whether to make a one-size-fits-all design that is useful for many types of surgery or to tailor a system to a specific type of surgery. The da Vinci surgical system falls to a great extent into the first category. Until now, it has been successfully used in many surgical areas, including urology, gynecology, cardiac surgery, and thoracic surgery (76). Other types of surgery are currently being explored (77). In the subsections below, we present some of the robotic systems that are designed for a specific type of surgery. We focus here on the human–robot interaction considerations of these special-purpose robots and how they are met in the robot's design. The set of robotic systems discussed here is by no means exhaustive but does show some of the variations in the requirements and designs across several areas in robot-assisted surgery. We categorize the work in this area based on surgical specialty. **Figure 2** shows an overall schematic diagram of some of these systems and their uses.

3.1. Urology and Gynecology

Due to the difficult anatomical access to pelvic organs, robots have become commonplace in urological and gynecological procedures. Before the advent of minimally invasive surgery, these procedures required large incisions to access the anatomy, which carried risk for significant blood loss and long recovery times. The rates of such complications dropped following the introduction of laparoscopic surgery, but the tools used are unwieldy (79, 80). The adoption of robotics in this field has been spearheaded by the da Vinci surgical system, which has a range of benefits over traditional laparoscopic techniques. As a teleoperative robotic system, it has much more intuitive navigation due to its mitigation of the fulcrum effect typically experienced with laparoscopic tools, in which the tool tip moves in the opposite direction to the surgeon's hand (81). The system also scales down motion, allowing for fine maneuvers; mimics the human wrist using EndoWrist

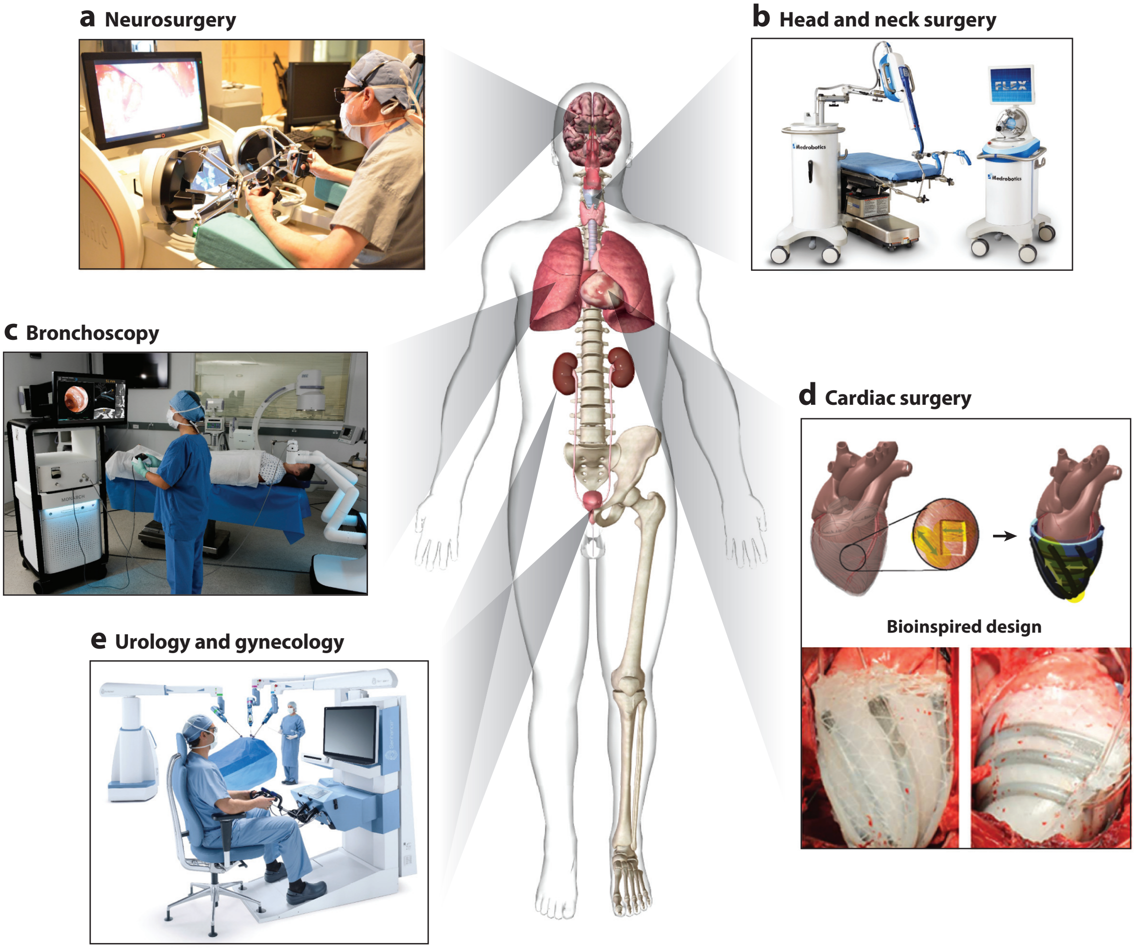

Figure 2

Area-specific medical robotic systems in clinical or clinical study use. The 3-D anatomical model in the center was created with BioDigital Human (**http://www.biodigital.com**) and used with permission. (*a*) The neuroArm robotic system for neurosurgery. Image courtesy of Project neuroArm (Medical Robotics Program, University of Calgary, Calgary, Canada) and used with permission. (*b*) The Flex robotic system for head and neck surgery. Image courtesy of Medrobotics Corporation and used with permission. (*c*) The Monarch platform for bronchoscopy. Image courtesy of Auris Health Inc. and used with permission. (*d*) A soft robotic sleeve to support heart function. From Reference 78. Reprinted with permission from AAAS. (*e*) The Senhance surgical system for urology and gynecology. Image courtesy of TransEnterix Surgical Inc. and used with permission.

instruments with seven DOFs; and eliminates hand tremor. A stereoscopic endoscope that provides depth perception and can be directly controlled by the surgeon enhances visualization over traditional laparoscopic techniques (82). Common procedures using the da Vinci include robotic prostatectomy, cystectomy, hysterectomy, and nephrectomy procedures, among others (76). Despite the benefits of the da Vinci system of improved dexterity and visualization of the surgical field, these procedures still pose problems in tissue/object detection, as visual recognition of anatomical features is an important yet difficult task. To tackle this challenge, groups have developed robotic systems that integrate with the da Vinci to provide image guidance during robotic surgery.

Ultrasound is an imaging modality that is well suited for image guidance during robotic procedures. It can image anatomy in real time, is free of ionizing radiation, and is relatively inexpensive. Its use for guidance during prostatectomy has been investigated over the past 15 years. Ukimura and colleagues (83, 84) have shown that transrectal ultrasound can be used to visualize the prostate and surrounding structures during robotic prostatectomy. Leveraging this finding, Han et al. (85) and Kim et al. (86) developed a joystick-controlled robot that sweeps the transrectal ultrasound transducer to image different planes of the prostate and surrounding tissues. While the joystick gives the surgeon direct control of the sweep angle, it also adds another degree of complexity that the surgeon must be constantly aware of. Adebar et al. (87) proposed a robotic system that tracks the da Vinci surgical instruments and uses the tip of one of the tools as a 3-D cursor in order to control the sweep angle directly from the master manipulators in the surgeon's console. This system has since been updated to use preoperative MRI intraoperatively via MRI–ultrasound fusion (88, 89). This fusion helps further improve decision-making, as MRI has excellent cancer detection capabilities (90) but cannot be used to image in real time. The fused MRI is displayed on the surgeon's console using TilePro, a capability of the da Vinci system that allows external inputs to be displayed alongside the endoscopic view, avoiding the need for surgeons to look at multiple screens to synthesize data. Intraoperative studies using this MRI–ultrasound fusion were conducted on seven patients. A similar study on 70 patients from Porpiglia et al. (91, 92) used TilePro to display a rendered prostate model from a segmented MRI that was aligned to the endoscopic video feed to provide an augmented-reality view of the surgery. Both of these systems used TilePro to streamline the human–robot interaction.

In gynecology, the da Vinci system is widely used for endometriosis resection, hysterectomy (removal of the uterus), and myomectomy (removal of uterine fibroids). To reduce the risk of injury to the ureters and bladder, uterine manipulators are often used to maneuver the uterus to improve exposure of the surgical field during dissection. While manual manipulators exist, they require an operator (93). VIKY UP (Endocontrol, La Tronche, France) is a commercially available robotic uterine positioning platform that is controlled with voice commands and designed to replace the tasks of an assistant during robotic procedures using the da Vinci. Similar to the company's VIKY endoscope positioning robot (94), the VIKY UP has a conical workspace due to its remote center of motion located at the patient's cervix. The system was first used in a pilot study of 36 patients in 2013, which concluded that the device was safe and easy to learn and use (95).

Following the success of the da Vinci robot, other minimally invasive surgeon extender robots have been approved for clinical use. One example is the Senhance robotic system (TransEnterix, Morrisville, North Carolina, USA), which was initially approved for gynecological procedures (96). Unique features of this system include haptic feedback to the surgeon through laparoscopic-type manipulators, independent robotic arms, and infrared eye tracking to position the endoscope (97). This last feature aims to further streamline the human–robot interaction by allowing camera repositioning without stopping the surgery.

Robots working under supervised autonomy have also been used in urology. The AquaBeam system (Procept BioRobotics, Redwood City, California, USA), is an autonomous robot that uses a water jet to resect prostatic tissue as a treatment for benign prostatic hyperplasia. The robot consists of a console, a robotic hand piece, and a single-use probe (98). To perform the procedure, the water jet probe is inserted transurethrally. An ultrasound volume is acquired using a transrectal ultrasound transducer mounted to a stepper motor, and the surgeon creates a procedural plan by contouring the tissue to be removed. Based on this plan, the robot then automatically controls the water jet's flow rate and rotational and longitudinal movement to resect the tissue. At any moment, the surgeon can interrupt the procedure via a foot pedal. Prior to FDA approval in 2017, clinical studies on 282 patients were carried out (98, 99).

Also leveraging transurethral access, Hendrick et al. (100) developed a handheld robot that employs concentric tube manipulators to treat prostatic hyperplasia. Using an interface consisting of a screen displaying endoscopic video and a joystick for each manipulator, the surgeon guides the concentric tubes for laser resection of the prostate. The robot is mounted on a counterweighted arm to aid the surgeon in manipulating the handheld system in six DOFs. Evaluations were carried out both in phantoms and on cadaveric specimens.

3.2. Orthopedic Surgery

Orthopedic surgery, the branch of surgery pertaining to the musculoskeletal system, is a popular application of robotic technology. Due to the rigid nature of the skeletal anatomy, bone can be treated as a fixed object, allowing for simplified control paradigms and high accuracy and precision compared with nonrobotic techniques. This is especially important because small errors in implant location or screw placement can have adverse affects on quality of life, such as increased pain or an abnormal gait. Unlike the da Vinci and other general surgery robots, orthopedic robots must also be able to account for high forces and stiffness not typically associated with soft-tissue procedures. Current clinical systems are used mainly in procedures for joint replacement, which involves milling bone for the fixation of implants, such as total hip arthroplasty and partial or total knee arthroplasty. The main advantages of using robotic systems for orthopedic procedures include enhanced reproducibility, improved implant stability, and less resulting pain for the patient (101, 102). More in-depth discussions on orthopedic robots from a clinical perspective have been previously published (102, 103); here, we focus on how these systems address human–robot interaction.

Computer-aided orthopedic surgery systems consist of four basic elements: 3-D modeling (i.e., generating virtual objects), registration, navigation, and referencing (i.e., fiducial tracking for motion compensation) (104). These four elements play an important role in the human–robot interaction in orthopedic surgery. The first step involves creating a virtual object to plan the procedure. This is typically done using preoperatively acquired CT scans, due to the modality's excellent geometric accuracy; 3-D models of the bone can then be extracted and displayed to planning software, where a surgical plan can be developed. Virtual objects from preoperative images, however, are not always accurate due to changes to the anatomy over time, so the use of motorized C-arms (105) and the O-arm (Medtronic, Minneapolis, Minnesota, USA) intraoperatively has been proposed to produce these objects. Once the virtual object has been created, it must be registered to the patient and the robotic system. This is typically done using a probe that is either optically tracked or attached to a robotic arm to define points in the patient's anatomy to match to points in the virtual object.

The most variation in the human–robot interaction occurs during navigation. Navigation in active autonomous systems, such as the TSolution-One system (THINK Surgical, Fremont, California, USA) and its precursor ROBODOC, is based on principles of computer-aided design and manufacturing in that the robot follows a predetermined path (14). In this system, the end effector automatically mills bone by moving the cutting tool around the workspace according to the plan devised from the virtual object. It can be used for both total knee arthroplasty (106) and total hip arthroplasty (107). By contrast, passive systems such as the Mako robotic arm (Stryker, Kalamazoo, Michigan, USA) allow the surgeon direct control over bone resection. Using a robotic arm, surgeons can move the cutting tool around the workspace themselves. The robot creates a virtual fixture, limiting the workspace to only the predefined area so that no excess bone is removed. NAVIO (Smith & Nephew, London, United Kingdom) similarly restricts bone resection to a predefined plan. Where it differs from the Mako is that the surgeon's tool is freehand and its cutting burr is automatically retracted and extended to cut only the planned bone.

3.3. Cardiac Surgery

As mentioned above, navigation is one of the main challenges facing surgeons during robotic surgery. Navigation becomes even more difficult in cardiac surgery because of the continuous movement of the heart and the continuous flow of blood, which obstructs the field of view. Fagogenis et al. (17) tackled this problem by proposing a method to perform autonomous navigation using a robotic catheter inside a beating heart filled with blood. The target procedure is leak closure, which the surgeon handles by first extending a guide wire from the catheter to the leak and then deploying an occluder to close it. In the proposed method, the navigation part of the task is carried out autonomously, and once the catheter reaches the target location, the surgeon takes the lead and performs the rest of the task manually. The navigation algorithm, called wall following, generates low forces on the walls of the heart and then follows these walls to navigate through it autonomously; it was inspired by insects, which use a similar idea when navigating low-visibility environments. The authors conducted multiple in vivo porcine experiments to autonomously navigate the catheter to multiple regions in the heart, and their results showed that their proposed autonomous system performs comparably to an experienced clinician.

The work of Fagogenis et al. (17) presents some interesting aspects of human–robot interaction. First, it is an example of the traded-control paradigm in human–robot interaction: Part of the task (the navigation) is performed by the robot autonomously, and the riskier part that requires more dexterity (fixing the leak) is conducted by the human. This approach demonstrates the philosophy that autonomy in surgical robots can follow the same pattern as in aviation, where pilots take control only during the critical steps, and the rest is handled by the autopilot. Moreover, the authors presented a different view of autonomy in surgical robotics: Instead of aiming for robots that perfectly execute a complete task autonomously, robots can be designed such that they know when they become stuck during task execution and can ask the humans for help. This view raises some interesting questions related to human–robot interaction, such as how the robot can know that it needs help, how it should ask for help from the surgeon, and how the surgeon should provide the help.

Another direction in the use of robotics for heart surgery is building systems to support the function of the heart, e.g., in the case of heart failure. In such a case, the heart is unable to pump sufficient blood to the body, which can lead to serious consequences, including death. To address this problem, Roche et al. (78) proposed a soft robotic device that supports the function of the heart. This device can be used by people with serious heart failures until a heart transplant procedure becomes possible. The design of the soft robot is inspired by the arrangement of the muscle layers in the heart and allows twisting and compressing motions similar to those of the heart. The user interface consists of a computer with a custom graphical user interface, an electropneumatics control unit, a data acquisition card, and a pacemaker. The interface receives data about physiological parameters such as heart rate and can be used to control the twisting and compressing motions of the soft robot and hence regulate the blood flow level. The proposed device has been tested in vivo on six swine and five rats.

The above work highlights the benefits of using soft robots in surgical applications, especially those involving physical human–robot interaction, with the human here being the patient. These robots enable close physical interactions with humans without raising too many safety concerns and can mimic the motions of soft tissues, enabling their use inside the body to restore some of its functions. Their design and use are currently an active area of research (108).

3.4. Head and Neck Surgery

One of the main challenges in head and neck surgery is the difficult access and limited available workspace for procedures on the pharynx (109), larynx (110), and nasopharynx (111). Due to this limited workspace, flexible and articulated robots can be very beneficial in this type of surgery (112) and can lead to better patient outcomes.

In addition to the da Vinci surgical robot (113), other platforms are in use or under development for head and neck surgery. Among these is the commercially available Flex system (Medrobotics, Raynham, Massachusetts, USA) (114), which was approved by the FDA for ear, nose, and throat applications in 2015 and for colorectal procedures in 2017 (96). The device setup is similar to conventional endoscopy, where the surgeon holds the surgical tools and directly controls them. The main difference is that the tools and endoscope are flexible and can be articulated to reach hard-to-access regions, which is one of the requirements in head and neck surgery in general. The second difference is that the flexible endoscope is controlled with a joystick-like controller, which is easier to use than a conventional endoscope. In short, the core advantage of the user interface lies in the flexibility of the surgical tools and endoscope. The Flex system has been successfully used in many areas in head and neck surgery, including the pharynx (115) and skull base (116).

3.5. Neurosurgery

One of the early robotic systems to be used in neurosurgery is the Neuromate (Renishaw, New Mills, United Kingdom) (117), a commercially available system that has been used in thousands of patients (118). The Neuromate is a supervised autonomous arm robot that uses preoperative CT and MRI images to generate a plan to reach the target inside the brain. It also uses ultrasound imaging to track the head movement and adjust the plan accordingly. The tracking is carried out by using fiducial markers implanted in the patient's head.

A more recent system used in neurosurgery is the neuroArm (119), an MRI-compatible master–slave robotic system from the University of Calgary. Using a master workstation, the surgeon controls two slave robotic arms that copy his or her hand motions. The user interface includes tremor filter and motion scaling to precisely control the robot's movements and provides the surgeon with haptic feedback from forces measured using strain gauges. At the master workstation, the surgeon can see the surgical site in 3-D, and images from other modalities, such as the MRI, appear on other dedicated monitors. In addition to the main surgeon at the master workstation, the system requires a surgical assistant next to the slave component; the main surgeon and the assistant communicate using headsets. The system has been used in more than 58 patient cases (118).

3.6. Radiotherapy

Radiotherapy refers to the use of ionizing radiation to destroy selected tissues (120). It is used mostly to treat cancer, including brain, lung, liver, and spinal cancers. One of the main requirements of this type of therapy is to maximize the radiation dosage on the cancerous or damaged tissue while minimizing the effects on the healthy ones. Robots have proven useful in a range of radiotherapy applications, including stereotactic radiosurgery and brachytherapy.

Stereotactic radiosurgery is a specialized type of radiotherapy that focuses radiation beams at targeted tumors under image guidance. The CyberKnife (Accuray, Sunnyvale, California, USA) is a commercially available image-guided robotic system that has been used in radiosurgery (57) in more than 100,000 cases worldwide (121). It consists of a six-DOF robotic manipulator with a linear accelerator designed for radiosurgery mounted on it (122) and uses preoperative and intraoperative images of the patient to deliver the treatment beam to the target location with submillimeter accuracy (123).

The interaction between the surgeon and the CyberKnife falls under the category of supervised autonomy (48). The interaction starts with the surgeon identifying the areas of interest based on CT or MRI scans of the patient, and the device then generates a motion plan so that these areas are exposed to the maximum dosage possible. The medical physicist must approve this plan, and once it has been approved, the CyberKnife will move according to the plan. The patient does not have to be fixed; instead, the device tracks the patient's motion based on external markers on a vest worn by the patient. The CyberKnife is currently the most autonomous system that has been approved and used on patients (12).

A related area is brachytherapy, which refers to the implantation, via needles, of radioactive seeds in or near the target pathology to treat cancer. Applications include the treatment of prostate, breast, and lung cancer, among others (124). Due to the precision required in seed implantation, robotic systems have been developed for robust and repeatable results. One example is a robot from Hungr et al. (125), who proposed a 3-D MRI–ultrasound fusion platform. As discussed above, MRI fusion enhances cancer visualization, while ultrasound allows for real-time anatomical imaging to identify seed targets and needle trajectory planning. Using a five-DOF needle positioning system and a two-DOF needle insertion module, the system can accurately insert the needle to the targeted region.

3.7. Bronchoscopy

One of the emerging application areas for robots is bronchoscopy, which refers to the procedure of examining lungs and air passages using an endoscope to look for lung cancers, infections, and diseases (126). In general, the procedure is performed by inserting an endoscope through the patient's mouth and navigating the lungs to reach a target location (127). Applications of this technique include performing biopsies of peripheral lung lesions and lymph nodes and placing markers to be used later in radiation therapy or surgery (128, 129). In this context, a major goal in bronchoscopy is to facilitate the navigation process. One way to achieve this goal is by incorporating several imaging modalities; another is to use a flexible endoscope that can easily navigate through the entire lung. These features exist on some recently released commercially available systems.

One such system is the Monarch platform (Auris Health, Redwood City, California, USA), which was approved by the FDA in 2018 to be used in bronchoscopy for diagnostic and therapeutic procedures (130). The teleoperated platform consists of three main components: the bronchoscope, tower, and cart. The bronchoscope consists of an endoscope inside an outer sheath. It is a thin articulated structure (only millimeters in diameter), providing the needed flexibility for navigation. The navigation in the Monarch platform is based on an electromagnetic field from a generator interfaced with the cart. The tower contains a monitor that clinicians use as a navigation display. Clinicians use a video-game-type handheld controller to control the movements of the bronchoscope (131). The system allows the clinician to choose a target location on the navigation display, and then the system can generate a path toward it; the clinician can always modify the generated path as necessary. This is an example of how the consideration of navigation challenges faced by surgeons and clinicians can improve the interface design of medical robotics and hence improve the human–robot interaction to achieve the clinical goal.

Another commercially available system is the Ion system (Intuitive Surgical, Sunnyvale, California, USA), which was approved by the FDA in 2019 for minimally invasive lung biopsy. The navigation in this system is based on shape-sensing technology and is designed to seamlessly integrate into the current workflow of lung biopsy and other standard imaging modalities used in these procedures (132). The Ion system has been used successfully on 30 patients (133).

4. OPEN PROBLEMS AND FUTURE OUTLOOK

4.1. New Applications, Interfaces, and Interactions with Robots In Vivo

Multiple areas in surgical robotics are expected to have a major impact on the development of the field itself and on society in general. These areas include automation and robotic implants (134, 135).

Automation has shown great promise in some commercially available systems, such as the CyberKnife in radiosurgery and ROBODOC in orthopedic surgery, but it has not yet been used in commercial systems for other types of surgery, partially because of the associated regulatory and ethical issues (136). That is why an important research problem is to first define new application areas where autonomy can benefit the surgical practice. Lower-risk tasks, such as moving an endoscope (137), can be potential first examples of tasks that can be automated and tested in vivo. In the short term, more shared-control and traded-control methods can be employed in vivo to gain the gradual acceptance of such systems by surgeons. Learning from the outcomes of these systems can pave the way to go further with automation in the long run.

Another exciting and promising application area is that of robotic implants inside the human body. Such robotic implants can interact with tissues inside the body and respond in a meaningful way to physiological signals in tasks such as tissue regeneration (138) and organ replacement (139). More applications for this area need to be identified, along with solving issues related to the biocompatibility and adaptability of these implants based on the physiological changes inside the human body.

It would be interesting to see how humans—both surgeons and patients—would interact with these promising application areas. For example, it would be interesting to understand the best way of decomposing a task into an autonomous part executed by the robot and another part executed by the surgeon when using traded-control methods. The role that novel types of interfaces, such as gloves, head-mounted displays, and robotic exoskeletons, would play in these areas is also underexplored (82). Finally, studying human-related aspects such as trust and privacy is important to understand the effect of these technologies on society as a whole (140, 141).

4.2. Unified Frameworks for Rapid Testing and Prototyping

One important area for future research is the development of tools and frameworks that can enable rapid prototyping and testing of research ideas in surgical robotics. This area is motivated by some of the successes of the existing platforms in the field, most notably the da Vinci Research Kit (dVRK) (142). The dVRK is a collection of hardware and software components that allows the use of a first-generation da Vinci surgical system as a research platform. It is currently being used by more than 30 research groups worldwide and has led to many significant research contributions. It is also an example of the collaboration between research groups and industry to advance the development of the field, and we believe that similar collaborations with other leaders in the industry will make platforms in other areas of surgery available for researchers to develop and test their research ideas. Other examples of the available research platforms include the Raven surgical robot from the University of Washington (143) and MiroSurge from the German Aerospace Center (144).

In the research community, there is also a need to build more software frameworks to prototype and test several human–robot interaction scenarios in surgical robots. For example, Nichols

& Okamura (145) proposed an open source software framework to test several collaboration strategies between humans and robots for multilateral manipulation tasks in surgical robotics. Using their framework, researchers can test the effects of using different levels of automation on human–robot interaction while performing a surgical task. Another example comes from Cubrich et al. (146), who proposed a robotic platform for single-port surgery. They designed their software architecture in a modular way to provide an environment for rapid prototyping of new technologies, such as autonomy, augmented reality, and telesurgery. Enayati et al. (147) built an open source framework to be used for augmented-reality teleoperation applications on the dVRK and used it to test, in a virtual environment, methods to improve training in surgical robots. Such frameworks are important to first test new ideas virtually before testing them on robots with humans. There is a need to develop more of these frameworks and make them available for the rest of the community.

To build on the current trend of applying machine learning methods (148), it is important to collect and share relevant data sets of robotic surgery in the community. The only publicly available data set for robot-assisted surgery is the one from Johns Hopkins University (36), which contains motion data from a small number of surgeons. Collecting a more extensive data set from a larger number of surgeons across several medical centers will open up more possibilities of using complex machine learning algorithms for several applications in surgical robotics, such as training and automation. Sharing these data sets with the community is a step toward benchmarking the research efforts in this area (149).

4.3. Collaboration Between Surgical and Robotics Research Communities

To enhance the interaction between engineering researchers and the surgical community, we recommend identifying more surgical problems where robots can provide a good solution. We envision a repository of these problems on the internet available for researchers. This repository would contain a brief description of the surgical problem suitable for engineering researchers, in addition to clinical requirements for any proposed solutions. Interested engineers can then think of tools from the engineering or robotics toolbox that can be helpful in solving these problems and meeting the requirements. As a first step, we envision having more research challenges at the major conferences in this area that consider some of these problems and organize competitions among interested researchers, similar to those at the major robotics conferences (e.g., the IEEE International Conference on Robotics and Automation). Such initiatives can help accelerate research, attract new researchers, and allow them to apply their knowledge in this exciting area.

5. CONCLUSION

The use of surgical robots in vivo has changed (and continues to change) surgical practice, bringing many benefits for patients all over the world. In this article, we have discussed the design requirements for these robots from the point of view of human–robot interaction. We presented the clinical requirements of surgical robots along with the technological aspects needed to satisfy them. We highlighted the major challenges surgeons face during robot-assisted surgery in addition to the necessary precautions to ensure safety during surgical procedures. We then showed how these requirements are met across several different surgical specialties: urology and gynecology, orthopedic surgery, cardiac surgery, head and neck surgery, neurosurgery, radiotherapy, and bronchoscopy.

We believe that autonomy and robotic implants represent the next frontier in surgical robotics and their use inside the human body. Further collaborations within the surgical robotics community and with other relevant communities (e.g., surgical communities) are needed to identify clinical problems that can benefit from innovative solutions in robotics. We have highlighted the need to build and share frameworks for rapid testing and prototyping of novel research ideas to accelerate innovation in this exciting field.

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