

State-of-the-art of intelligent minimally invasive surgical robots

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Abstract A number of developed countries are rapidly turning into super-aged societies. Consequently, the demand for reduced surgical invasiveness and enhanced efficiency in the medical field has increased due to the need to reduce the physical burden on older patients and shorten their recovery period. Intelligent surgical robot systems offer high precision, high safety, and reduced invasiveness. This paper presents a review of current intelligent surgical robot systems. The history of robots and three types of intelligent surgical robots are discussed. The problems with current surgical robot systems are then analyzed. Several aspects that should be considered in designing new surgical systems are discussed in detail. The paper ends with a summary of the work and a discussion of future prospects for surgical robot development.

Keywords robot history; medical robot; surgical robot; radiofrequency ablation; organ model

Introduction

Personal robots have long been expected to be used in practical applications. However, this expectation has yet to materialize because of two factors. First, no actual market for such robots exists despite the society's growing need for them. Second, the required peripheral technology and maintenance of the social infrastructure are insufficient and do not allow robots to play an active role. For robots to operate effectively as partners to humans, they must be well integrated into parts of social systems. Appropriate preparations have been made in the 21st century. A strong demand also exists for real robots to act as good human partners in many fields, including robot-assisted surgeries.

Most developed countries and a number of developing countries, such as China, are now facing the problem of aging populations [1–3]. Increasing numbers of elderly people mean a relative reduction in the number of available assistants. Health and security are the top concerns of developed countries with rapidly aging populations. The development of the industry required to achieve these health and security aims is considered promising. The development of specialized medical aid equipment has enabled bedridden patients, wheelchair users, and other

types of patients to live independent and rewarding lives. The use of new surgical equipment also reduce pain and improve patients' subsequent quality of life.

The increase in the elderly population has expanded the market for robots, and much technological progress has been achieved in the past 30 years. Therefore, the potential use of medical robots in the future is promising. One specific branch of medical robotics, that is, surgical robotics, has undergone major development. Surgical robotics is expected to generate a huge market in the future. Given the complexity of the human body and the differences between individuals, along with the empirical differences between doctors, surgical robot systems are projected to act as partners to doctors to help them perform surgeries efficiently, safely, and easily. However, most current surgical robot/tool systems are simply tools for doctors. The robots are not aware of the surgical requirements or those of individual doctors. Ideal surgical systems should be able to deal with misoperations by surgeons and make appropriate suggestions to guide and support surgery. We define these ideal systems as intelligent surgical systems. These systems should serve as a powerful tool to help society deal with aging human populations.

The current study provides an overview of current intelligent surgical robots and focuses on three surgical systems with wide usage ranges. Providing a background description of the development of robot technology before

discussing intelligent surgical systems is essential because the development of surgical robots is closely related to the overall development of the robotics industry. This paper is structured as follows. The second section introduces a concise history of robot development to provide readers with a rich overview. The third section discusses several of the main intelligent surgical robots. The technical characteristics, advantages, and disadvantages of these robots are also analyzed in detail. Based on the second and third sections, the fourth section proposes and analyzes the aspects that should be considered in the design of new surgical robotic systems. The final section details the conclusions drawn and future perspectives.

Brief review of robot history

Advances in robotics have led to innovations in surgical methods. The demand for medical applications has also promoted the overall advancement of robotics. Japan has long held a prominent position in the field of robotics research, particularly since 1970. Robots for industrial, medical, and life support applications have been widely developed and applied in Japan. Therefore, the introduction to robots in this work mainly stems from the perspective of the Japanese history of robotics. Fig. 1 shows the chronological development of robotic technology, which can be divided into 10 stages. Representative robots and associated developments at each stage are introduced in the following sections.

The period before 1940 is referred to as the Age of Old Dreams of Robots. The ancient Chinese Wooden Ox and Gliding Horse [4] and the mechanical doll from the

Japanese Edo era [5] can be regarded as the earliest prototypes of robots. Subsequently, robots were drawn in comics. The fully automatic Astro Boy and the semiautomatic and remote-controlled Ironman No. 28 were popular among the Japanese people during that time.

From 1940 to 1970, the enthusiasm for the use of robots in industrial applications ballooned. Industrial robot development became a task for companies and research institutes. Thereafter, American research institutions began to develop industrial robots. The Versatile Transfer Machine [6] and Unimate [7] are representative robots that were developed during this period.

The period from 1960 to 1970 is regarded as the cradle period of robot development. In 1964, Waseda University began to research machine-controlled prostheses [8,9]. Around the same time, US companies such as GE developed prototypes for the current power suits and mobile robots for military purposes [10,11].

“The First Development Period” of Japanese robots took place from 1971 to 1975. In addition to Unimate, which was popular among many companies in the 1960s, Hitachi also developed an automatic casting robot in 1975 [12]. The automatic casting robot was the first robot that could control the height of a runner surface using a visual sensor on the factory line.

The late 1970s saw further development of industrial robots. For example, SCARA [13,14], a horizontal multi joint assembly line robot that was developed by Professor Makino of Yamanashi University, was popular among many companies for its precision work. Meanwhile, the United States developed a vertical articulated robot called the PUMA [15,16]. Outside the industry, robots were also used in other fields. For example, Matsushita pioneered the

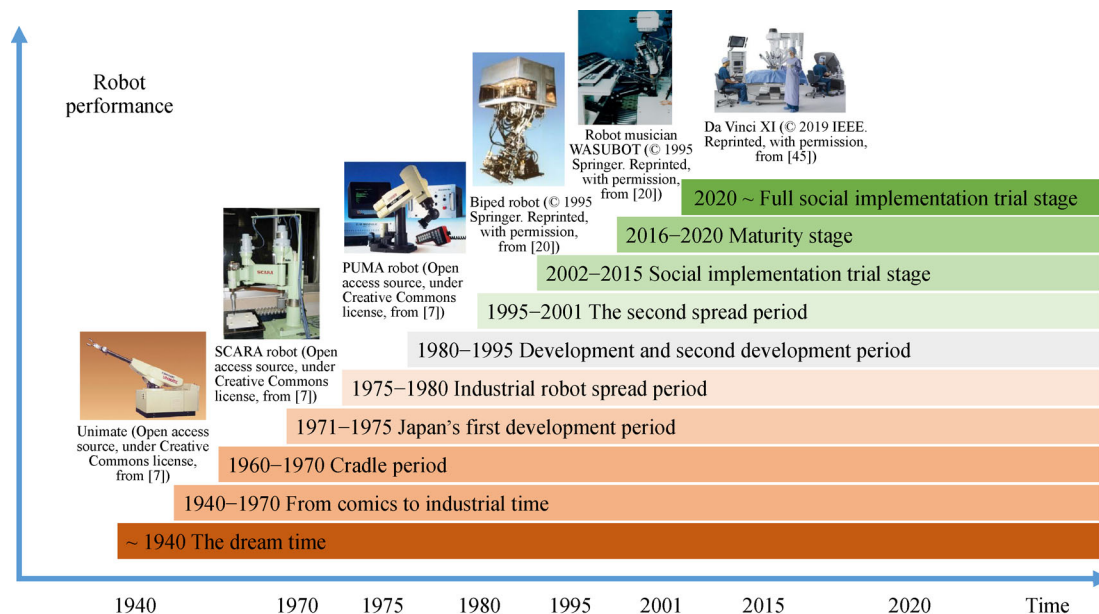


Fig. 1 History of robot development.

development of a communication robot called Tama [17,18] while Secom developed a food assistant robot named My Spoon [19].

The period from 1980 to 1995 is regarded as the second development period where Japanese companies competed in the development of various robots. Japanese companies presented a biped robot [20,21] and an automatic music playing robot [22,23] at the Tsukuba Expo in 1985. The development of extreme working robots [24] for use in nuclear power plants led by the Ministry of International Trade and Industry, along with the development of cleaning robots that could be used in ordinary office spaces, was also noted during this time. During the same period, Carnegie Mellon University made progress in the development of autonomous vehicles, and their car crossed the US in 1995 [25]. In addition, agricultural robots were developed at Ohio State University [26]. At the same time, minimally invasive surgical robots received increasing research attention, and their development progressed. Minimally invasive surgery in the form of endoscopic management of upper urinary tract stones was first proposed and performed in the UK in 1985 [27]. More than 500 renal and ureteric calculi were removed using this method, and the high levels of success and low complication rates verified the superiority of such minimally invasive surgery. Since then, a variety of minimally invasive surgical tools and systems [28–31] have been developed worldwide.

The second spread period for Japanese robots ran from 1995 to 2001. Continuing technological development brought advances in robotics and led researchers to pursue efficient and safe medical services. However, at that time, robot-assisted surgery was based entirely on doctors' experience. Therefore, the development of intelligent surgical robot systems that could be used easily, regardless of doctors' skill level, then became a hot research topic. A result of this requirement was the da Vinci surgical auxiliary robot [32] that was launched in 2000. A year later, a remote transoceanic surgery was performed successfully using the ZEUS surgical robot system [33]. During this period, significant progress was also made in robot systems for application in other fields. A robot developed by Hitachi Ltd. was loaded into space via a space shuttle in 2000 to work on the International Space Station. From this time onward, the development of walking support robots for the elderly and home cleaning robots, such as the Roomba [34], became popular. With this background, the Joba [35] robot was developed by Panasonic in cooperation with the National Rehabilitation Center for the Disabled of Japan. However, because of its high cost, this robot did not become popular. At the same time, the RodeoBoy rehabilitation robot [36] made in China made progress in terms of popularization because of its high quality and low price.

Various types of robots were used in a range of fields

during the period from 2002 to 2015. In Japan, teleoperation-type construction machines were developed and tested [37]. In the United States, Boston Dynamics made progress in developing the Big Dog [38] transport robot for the US Department of Defense. During this period, humanoid robots also became a focus of research and development. Professor Hiroshi Ishiguro developed a humanoid robot named the Geminoid HI [39], which resembled Professor Ishiguro, including his voice and head movement.

Japan's robotics technology has matured since 2016. The full-scale social implementation of robots is anticipated to begin after 2020.

Major types of intelligent surgical robots

With the continued advancements in robotics, great strides have been made in the development of surgical robots since the end of the last century, particularly in some developed countries that are facing super-aged societies. At present, many different types of surgical robots and surgical equipment have been developed with the aim of reducing operational difficulty and improving the quality of surgery. Robot-assisted surgery using these devices involves opening one or a few holes in a patient's body and inserting the operating arm or arms into these holes to perform surgery. When compared with traditional open surgery, robot-assisted surgery results in low trauma and short recovery time. However, for surgeons, robot-assisted minimally invasive surgery often entails a steep learning curve because of the use of rigid or flexible but unstable instruments within an operating field that is only viewed indirectly via a monitor [40].

The ideal surgical robot should be smart enough to be a doctor's extended "arm" and exhibit flexible operability and controllability rather than simply being a scalpel in the doctor's hand. To achieve this goal, robot systems should have a certain "understanding" of the purpose of the surgery and necessary information about the surgery, including the surgical environment, planning, and key processes. The desired intelligent surgical robot systems are expected to identify a doctor's operations during surgery, improve the accuracy of cutting and stitching, and guide and plan the entire surgery.

At present, three main types of intelligent surgical robots have been widely reported or used: multiport laparoscopy robots (MPLRs), single-port laparoscopy robots (SPLRs), and robotic needle insertion systems (RNISs). In addition to these three main robot types, several special surgical systems for use in specific surgeries have been developed, and they include robot systems for brain tumor ablation [41] and invasive throat [42], eye [43], and nose [44] surgery.

The three main types of intelligent robot systems can be used in different fields and in various application scenarios.

Their advantages and disadvantages are shown in Table 1 along with representative works associated with these systems. Specific information about these robots is provided in detail in the following sections.

Multiport laparoscopy robots

When compared with conventional laparoscopy-type surgical instruments, MPLRs provide doctors with improved surgical perspective (i.e., a 3D field of view), enhanced maneuverability (five degrees of freedom (DOFs) or more in a single arm) and great surgical safety (e.g., use of a hand shake filter).

At present, the most popular and widely used surgical robotic system is the da Vinci surgical system developed by Intuitive Surgical. After obtaining US Food and Drug Administration (FDA) approval for surgery of the digestive system on July 11, 2000 [32], the scope of recognition of the system was gradually extended to thoracoscopic (thoracic) surgery, assisted incision cardiac surgery, urology, gynecology, pediatric surgery, stomatology, and otolaryngology. The da Vinci surgical system consists of an interactive operating platform for the surgeon, a multifunctional operating bed, and a surgical table. The surgical table contains three robotic operating arms (with five DOFs, including a two-DOF wrist) and one endoscope clamping arm. The system uses a master–slave control method, meaning that the surgeon can control the arms from the interactive operating platform. The latest model is the da Vinci XI (Fig. 2A), which has a force feedback function to give the surgeon an enhanced sense of immersion [45]. The best surgical system in the world is da Vinci. However, the system suffers from some drawbacks. Determining whether the arm is in contact with an organ or

with the patient’s abdominal wall is difficult because of the system’s limited field of view. Contact with an organ may cause organ damage, which would lead to serious medical problems. Another problem is that it is still necessary to open four holes in the patient’s abdominal cavity to perform surgery. In some cases where the surgical operating space is small, the da Vinci Xi surgical system cannot be used.

Another surgical system that has been used clinically is the ZEUS surgical robot system [33]. ZEUS was designed to assist in surgery and was originally produced by the American robotics company Computer Motion. This surgical system obtained FDA approval in 2001. The system has three robotic arms that can be remotely controlled. The surgical system also uses the master–slave control method. In 2001, remote cholecystectomy surgery was successfully performed on a 68-year-old female patient in Strasbourg, France, by a surgeon in New York using the ZEUS surgical support robot system [46]. However, the development of the ZEUS system was discontinued in 2003 after Computer Motion merged with Intuitive Surgical. ZEUS suffers from the same limitations for surgery in small operating spaces, and its lack of an effective force feedback method reduces its operational immersion experience [33].

A great deal of research has been carried out in the surgical robotics field in many research institutes. Other multiport robot systems have also been developed and reported. One such system is the Microhand [47], which was developed at Tianjin University on the basis of a master–slave operation mode with a force feedback function. Vascular suture experiments on a 3 mm carotid artery and on a leg artery of a rabbit (1 mm diameter) have been performed successfully using this system. Another

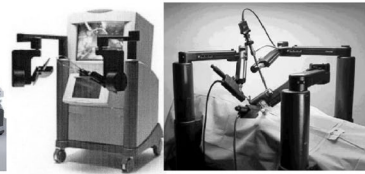
Table 1 Advantages and disadvantages of the three main types of intelligent surgical robots

Systems	Advantages	Disadvantages	Time	Scientist/Institution	Achievement
MPLRs	Minimally invasive	Multiple wound openings	2000	Intuitive Surgical, Inc., USA	Da Vinci
	High accuracy	Large operation space	2001	Computer Motion, USA	ZEUS
	Short recovery period	Limited field of view	2005	Tianjin University, China	Microhand
	Force feedback	Complex control system	2018	Deakin University, Australia	HeroSurg
High immersion	Collide with organ				
SPLRs	Minimally invasive	Limited field of view	2010	Waseda University, Japan	Dynamic vision field control
	High accuracy	Limited operation space	2013	Korea Advanced Institute of Science and Technology, Korea	Novel joint mechanism
	Short recovery period	Complex structural design			
	Force feedback	Complex control system			
	High immersion	Collide with organ	2016	Intuitive Surgical, Inc., USA	Da Vinci SP
Smaller operation space		2016	Waseda University, Japan	Dexterous manipulator	
RNISs	Minimally invasive	Needle deformation	2001	The University of Tokyo, Japan	CT compatible
	High accuracy	Human tissue deformation	2006	Waseda University, Japan	Liver insertion
	Short recovery period	Complex control system	2012	Waseda University, Japan	Breast insertion
	Precise navigation	Complex thermodynamic model	2019	Beijing Institute of Technology, China	CVC insertion

A Multiport laparoscopy robot systems



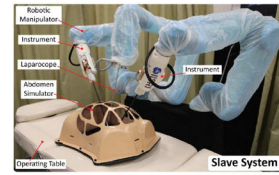
Da Vinci XI (©1995 IEEE. Reprinted, with permission, from [45])



ZEUS (©2003 IEEE. Reprinted, with permission, from [46])



Microhand (©2005 IEEE. Reprinted, with permission, from [47])

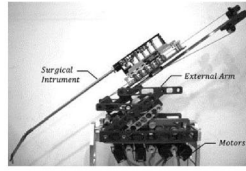


HeroSurg (©2018 IEEE. Reprinted, with permission, from [48])

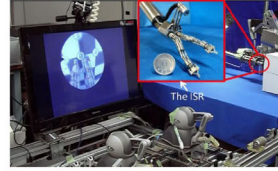
B Single-port laparoscopy robot systems



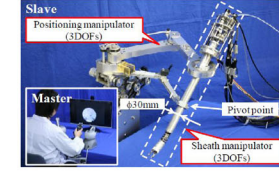
Da Vinci SP (©2019 Springer. Reprinted, with permission, from [50])



Single-port manipulator (©2013 IEEE. Reprinted, with permission, from [51])

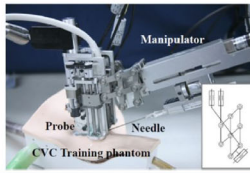


Single-port manipulator (©2013 IEEE. Reprinted, with permission, from [53])

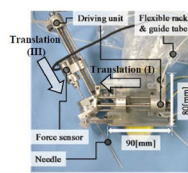


Single-port manipulator (©2011 IEEE. Reprinted, with permission, from [54])

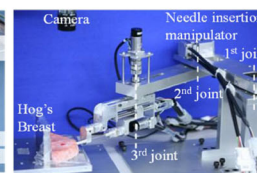
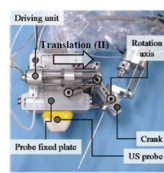
C Robotic needle insertion manipulators



CVC insertion manipulator (Open access source, under Creative Commons license, from [61])



Liver insertion manipulator (© 2009 IEEE. Reprinted, with permission, from [91])



Breast insertion manipulator (© 2012 IEEE. Reprinted, with permission, from [93])

Fig. 2 Several major types of surgical robots.

representative system, the HeroSurg surgical robot system [48] developed at Harvard University, is characterized by a tactile feedback system that can detect a surgeon's operating force in real time.

MLPRs can be used to perform a variety of surgeries. However, for some of these surgeries, the operational space for the robot arms is small. Thus, access has been inconvenient or even impossible for robots with multiple arms. Other MLPRs, such as da Vinci, use multiple wound openings to perform surgery. Although this approach reduces patient trauma and enables short recovery times relative to traditional open surgery, it still needs improvement. A single-port surgical system can solve these problems effectively.

Single-port laparoscopy robot

A single-hole surgical robot only needs to open one hole in the human body to achieve the insertion of all instruments, including both endoscopic and robot arms, during an operation [49]. The use of a single hole relative to the multiport approach is characterized by minimal surgical space requirements, reduced trauma, and fast postoperative recovery periods. In addition, single-hole surgical robots use few surgical consumables, are low in cost, and are

market-oriented. To make up for the deficiencies of the existing da Vinci surgical system in some applications, the da Vinci SP single-port surgical robot [50] was developed and is already being used in clinical practice. Other types of single-hole robot systems have also been reported [51–59]; however, almost all of them are at the research and development stage and are still far from actual clinical use.

The main disadvantages of single-port technology are the inadequate size of the operating triangle, instrument crowding, and operation arm collisions [49]. Single-port laparoscopic surgery is limited by the number of holes used. The relatively concentrated placement of the instruments hinders the formation of an operation triangle. The instruments can interfere with one another. Thus, the operation and the surgical field of view are affected. Additionally, the concentricity of the instrument and the light source affect the depth and distance perceptions of the surgeon to a certain extent, thereby increasing the difficulty of performing the operation.

Current research is mainly focused on the design of the mechanical structure and improvement of the control method to solve existing problems and improve the clinical availability of single-port robot systems. Shin and Kwon [51] proposed a novel joint mechanism for single-port surgical systems. Their system had six DOFs that could

avoid collisions between surgical tools and/or arms. The proposed structure can approach the surgical target more easily than conventional straight surgical tools. At the same time, this joint mechanism can prevent joint hysteresis and achieve accurate motion when using a large force. In another report [53], Liu *et al.* designed a dexterous manipulator (Fig. 2B). The device consists of three parts with a total of four DOFs: a linear motion joint (1-DOF), a bendable joint (2-DOF), and a rotational end effector (1-DOF). This manipulator is driven using a flexible shaft, and the end effector can perform bending motion in any direction. In single-port surgical robot-assisted surgery, the field of vision is one of the most important factors affecting surgical outcomes. Sekiguchi *et al.* [54] developed a prototype surgical robot with a dynamic vision field control function. They used positioning (4-DOF) and sheath (2-DOF) manipulators for vision field control and dual tool tissue manipulators (gripping, 5-DOF; cautery, 3-DOF) for surgery. Their vision control method combines “cut and vision field control” and “cut by vision field control” to enable fast surgery and improve the cutting accuracy.

Other current research is similar to the research described above and is intended to develop smart and safe mechanisms and convenient operating methods for single-port robot systems [57,59].

Robotic needle insertion system

Another type of intelligent surgical robot system is the RNIS. Unlike multiport and single-port robot systems, an RNIS inserts the required surgical tools into the target tissue to perform treatment directly. Thus, the smallest working incision is required. To reach the correct location and to conduct suitable treatments such as radio frequency ablation (RFA), the needle insertion system must solve the soft tissue deformation problem and understand the thermodynamic model of this tissue. Therefore, even with its lack of complex robot arms for operation by the surgeon, the robot system is still in high demand in terms of its design. Surgery assisted by an RNIS also offers important advantages with regard to reducing trauma and recovery time [60]. Percutaneous needle insertion has been widely used in central venous catheters (CVCs) [61] and in liver [62,63], lung [64], breast [65], and prostate surgeries [66,67]. With the rapid progress in medical devices and technology, increasing numbers of systems have been developed for use in percutaneous needle insertion surgery, as shown in Fig. 2C.

The two main challenges that are encountered by researchers in the development of percutaneous surgery systems are needle trajectory control and appropriate treatment operation after the needle reaches the target area. Of these two challenges, precise needle trajectory control is the most basic issue to be resolved. The surgery is only

likely to be successful if the needle can reach the correct location. The purpose of needle insertion is to prepare for surgical treatment, e.g., to conduct RFA or venous catheterization surgeries. To perform RFA well, the researcher must know and conduct research on the thermodynamic ablation model.

Needle insertion guidance

Medical devices that can generate images or video streams of the tissue to be inspected are used to guide the needle during the insertion process. These images or video streams allow the internal structure of the tissue to be observed, along with the spatial relationship between the needle and the tissue. At present, the most widely studied and used techniques for this purpose are computed tomography (CT), magnetic resonance (MR), and ultrasound (US) imaging [68–77]. Each method has its own advantages and disadvantages when used to guide needle insertion surgery.

CT technology uses computer-processed combinations of multiple X-ray measurements taken from different angles to produce cross-sectional images. A CT-guided needle insertion system should be used simultaneously with CT and therefore has several basic problems in surgical implementation. The first is the radiation problem faced by the patient and the doctor, both of whom are exposed to X-rays when CT is used to guide needle insertion in real time [78]. The second problem is that the surgical location must be fixed when using this system because the CT equipment is considerably large and must usually be placed in a separate room, but the needle insertion system still requires the cooperation of the CT equipment. The third difficulty is the limited size of the needle insertion manipulator and its operating space. A modern CT scanner has a bore with a diameter of approximately 60 cm, and the body part of the patient to be examined must be located within this bore during the examination process. Therefore, in the design and operation processes of the needle insertion manipulator, this space limitation should be considered carefully [68]. The final problem is image artifacts. Some material requirements should be considered in designing the needle insertion device because metal produces artifacts during the CT scanning process [79]. However, in certain percutaneous surgeries, such as nerve blocks and facet joint injections, CT imaging has been widely accepted as the guidance modality; therefore, CT-guided needle insertion is still needed for some applications despite the aforementioned disadvantages [69].

MR-guided needle insertion systems have similar problems to CT in terms of work space, the operation space for the needle insertion manipulator, and material requirements [70]. Compared with CT, MR imaging

(MRI)-guided needle insertion systems can provide better soft tissue contrast function, and neither the surgeon nor the patient need to worry about radiation damage [80]. Some materials [71,72], robot actuators [81,82], structures, and sensors [83,84] have been developed to ensure their compatibility with MRI.

Relative to CT and MR-based systems, US-guided needle insertion systems offer maximum flexibility in terms of design and use as the typical US device is small and moveable. US-based systems are thus ideal for needle insertion guidance.

Needle trajectory control

To control the position and trajectory of the needle tip precisely during the puncture process, researchers have investigated several important process parameters. A number of them studied the relationship between the needle deflection force and the needle penetration depth and built a force-deflection model [85,86]. Their experimental results indicated that the moment and rotational force acting on the needle should also be considered in the force-deflection model. Other researchers also investigated the needle trajectory during the puncture process in soft tissue and found that the infinitesimal force per displacement is a useful parameter for online trajectory generation [87]. Multiple experimental results also showed that the bevel tip angle strongly affects needle deformation [88,89] and that the introduction of a tissue model during needle insertion control will increase the accuracy of needle tip positioning [90].

Discussion

Most current surgical robotic systems and devices are still simply tools, and the success rate of surgical implementation depends on doctors' experience. Surgeons with limited experience find difficulty in using these systems because of individual differences and the lack of linearization of the human tissue model. In making surgical robots smart, the introduction of important information, such as the purpose of the surgery and the surgical environment, into surgical robot systems is necessary as such information enables these robots to correct any misoperation by doctors and provide appropriate suggestions at certain steps. Researchers should consider the following three aspects in introducing this information during the development of new surgical robot systems.

Quantification of physical characteristics of the human body

In the mechanical mechanics field, active research is now focused on small robots that can be inserted gently into a

patient's body. From this stage, the control of robots operating in close contact with humans will be dependent on the mechanical information acquired from the "human-object interaction" [91–94]. The basis for the acquisition of this information includes the mechanical mechanics, material mechanics, thermodynamics, and fluid dynamics. Regardless of the patient's race, age, gender, and the degree of their disease, the appropriate diagnosis and treatment should be performed by surgical robot systems. To achieve this goal, we need to express the biological model quantitatively and specifically. Surgical simulations must then be conducted in a virtual surgical environment using model reproduction technology to predict organ tissue deformation that might occur during operation. On the basis of the shape data of a patient's liver obtained from a preoperative diagnostic imaging system, a structural analysis method, such as the finite element method, can be used to construct a deformation model of the living body. At this stage, each parameter of the biological model can be set initially according to young healthy animal organs and then further corrected and improved using information from a database that stores various patient parameters using statistical processing [95,96]. In addition, boundary conditions are identified using image analysis or similar techniques from diagnostic images and are then set as the boundary conditions for the model. This type of method is called machine learning or deep learning. By performing simulations using the constructed model, searching for the optimum surgical insertion position and insertion angle is possible.

The construction of a biological model that can predict the deformation accurately based on material dynamics theory because the accuracy of deformation prediction during surgery is linked directly to the improvement of treatment accuracy. While many research groups have studied puncture plans, the evaluation models in many cases have been made from simple materials, such as silicon and gelatin [97–101]. However, the biological tissue to be modeled is complex and exhibits viscoelastic characteristics, which can be described using springs and dampers, and nonlinear stress and strain characteristics.

Deformation model and heating cautery model of organ tissue

The RFA technique has emerged as capable of reducing the physical and mental burden on patients because it does not require a large incision. This technique has been widely used to treat liver cancer by insertion of a needle into the cancerous tissue followed by the application of heat. However, when a needle is inserted into soft tissue such as the liver, the actual position of the cancerous tissue changes, thereby affecting the accuracy of the puncture. In addition, when cancerous tissue is cauterized by heating, the heat transfer process becomes complex because of

differences in the distribution of the peripheral blood vessels. As a result, controlling the burning range quantitatively is difficult, and some cancer cells may be left untreated [102]. These findings indicate that actual biomaterials are required in data acquisition and validation experiments. A schematic illustrating the establishment of a liver model is shown in Fig. 3.

If the organ tissue is simple, we can then use material mechanics as an approach for the numerical simulation of brain tumors. However, in recent years, the diagnosis and treatment of diseases in complex organs, e.g., breasts, prostate, lungs, heart, joints, blood vessels, and lymphatic vessels, along with newborns in the womb, have brought major challenges to medicine [103–105]. For breast cancer [103] patients, the softness of the breast tissue, the shape of the breast, and the location of the cancerous site during puncture treatment mean that the treatment effect is strongly influenced by the surgeon’s experience. Therefore, the establishment of advanced diagnostic systems and topical treatment techniques to reduce the physical, cosmetic, and mental burdens on female patients is necessary (Fig. 4) [103]. In addition to establishing the accuracy of the puncture site, researchers have also constructed thermodynamic/hydrodynamic models of the liver to aid in the implementation of RFA procedures. Achieving the aim of killing cancer cells requires a reasonable supply of heat from the RFA needle. The relationship between the applied heat energy and the energy that must be absorbed by cancer cells must also be determined on the basis of thermodynamic theory. Blood flow also affects heat distribution. Thus, the effects of blood flow must also be considered when constructing a thermodynamic model of tissues and organs.

Individual difference processing and control method

Normal organ model-based preoperative trajectory generation, the intraoperative acupuncture insertion angle, and the intraoperative correction procedure are related to a patient’s age, gender, medical history, daily environment, liver condition, and other factors. However, individual differences in liver stiffness and liver borders are not identifiable during the preoperative planning phase [106]. Modeling errors occur in pregenerated models because of individual differences between patients. Differences also exist between the behavior of model organs and the behavior of actual organs. Therefore, doctors can compare the information obtained during the surgery with their knowledge of organ characteristics obtained through experience. They can then perform treatment while applying the required intraoperative correction. For example, at the time of tissue puncture, the doctor recognizes the force transmitted to the liver by touch and performs the puncture procedure while estimating the hardness of the organ during the operation. To cope with the modeling errors caused by individual differences between patients, the computer analyzes the force information obtained during the operation via high-speed calculations and combines this information with the parameters of the biological model. Thus, a method is constructed to correct the boundary conditions of the model. In addition, the parameters and boundary conditions identified are used to enable the continuous correction of the insertion angle and the insertion position of the needle determined as part of the preoperative phase during the actual operation (Fig. 5) [106].

In addition to surgical robot systems, the individual

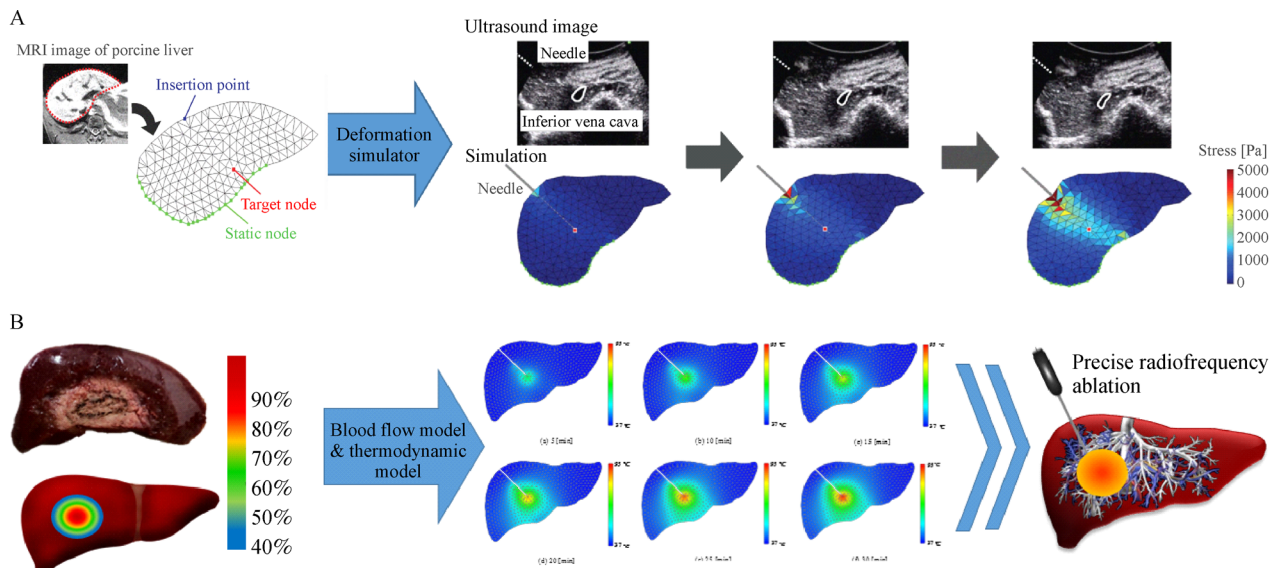


Fig. 3 Deformation model and heating cautery model of liver tissue. (A) Deformation of liver during needle insertion. (B) Temperature distribution of liver during tumor ablation.

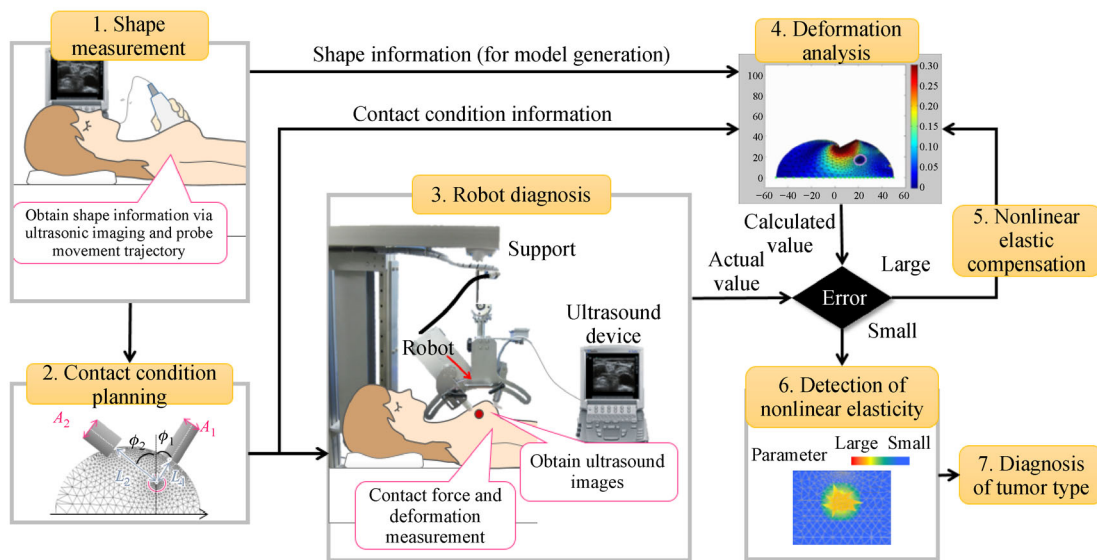


Fig. 4 Breast cancer diagnosis technology.

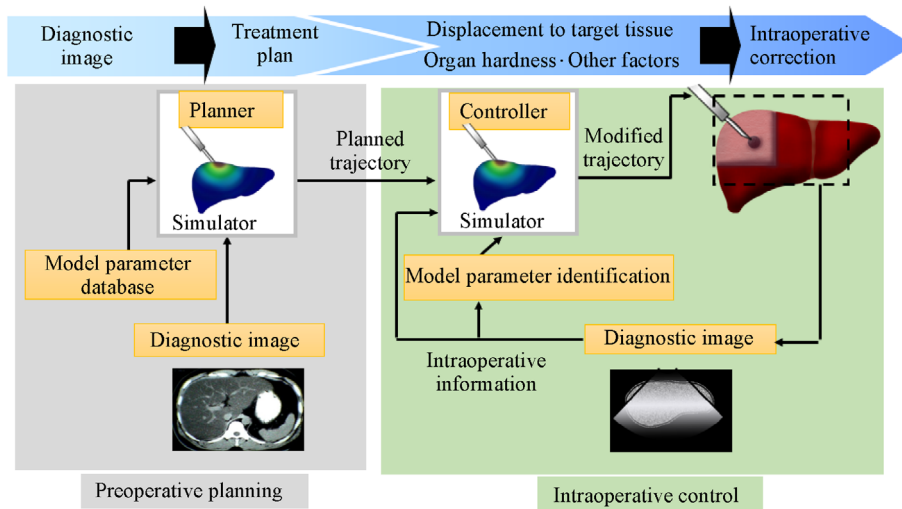


Fig. 5 Control method to handle individual differences. The difference between preoperative planned value calculated by the model and the actual value measured by the diagnostic device during surgery is repeatedly zeroed by convergence calculation (e.g., with a Karman filter).

differences between processing and control methods can be introduced to other medical robot systems, such as robot-assisted rehabilitation systems.

Conclusions

The problem of population aging is becoming an issue that most countries cannot avoid. A growing trend for robots to replace or assist humans in certain jobs exists. In the

medical health field, intelligent surgical robots and other medical robots combine to form a line of defense for human health. While some surgical robot systems, such as the da Vinci system, have already entered clinical use, most surgical robots are still under development. New technologies and new treatments are projected to be introduced into surgical robot systems to bring great well-being to human patients.

The advantages and disadvantages of current surgical robot systems are apparent. These systems can be used to

implement minimally invasive surgery to reduce patient pain and patient recovery time. However, with their limited field of view and operation space, surgical tools that protrude into patients may interfere with one another. In addition, the risk of contact between surgical instruments and other organs in a patient's body is also present. As a result of the complexity of the human body and the differences between individuals, robot systems and surgeons may be disturbed during surgery, and they may not always handle such disturbances well. Therefore, the incorporation of the entire surgical environment into the surgical decision-making process is necessary. We propose three aspects that could be introduced into the surgical process. Although these three aspects are closely related, each one is important and will be meaningful in improving the accuracy and reliability of robot-assisted surgery. Of the three aspects, the quantification of the physical characteristics of the human body serves as the foundation that provides preoperative planning information. The building of deformation models and heating cautery models of organ tissues can guarantee accuracy in minimally invasive surgery. Individual difference processing and control methods represent the final implementation, which ensures that robot-assisted surgery can be applied to any patient with high accuracy and reliability.

The technology of medical robotics is constantly improving. Other types of robots with great accuracy, efficiency, and flexibility have been reported, and they include cell-level minimally invasive surgical robots and soft robots [107–110], which may change the surgical approach in the future and benefit patients greatly. In the future, robotics will be widely applied in all aspects of life. We are committed to the use of mechanical engineering, materials mechanics, fluid mechanics, and thermodynamics to develop accurate and efficient surgical robots to cope with treatment of the elderly and improve the quality of life of surgical patients.

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Compliance with ethics guidelines

Masakatsu G. Fujie and Bo Zhang declare that they have no conflict of interest. This manuscript is a review article and does not involve a research protocol requiring approval by a relevant institutional review board or ethics committee.

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