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Review Article

Development status of telesurgery robotic system

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ABSTRACT

As an emerging field, telesurgery robotic system is changing the traditional medical mode and can delivery remote surgical treatment anywhere in the world. Advances in telesurgery robotic technology achieve the remote control beyond the current limitation of distance and special medical environment. This review introduces the development history, the current status and the potential in future of the telesurgery robotic system. In addition, it presents the construction of control platform and the application, especially in trauma treatment, as well as the challenge in clinic.

Introduction

Telesurgery robotic system refers to remote control of robot for surgery, which is an extension of surgery robot. Not only can it get over the restrictions of special areas including plateau, island, deep sea, underdeveloped areas of medical treatment, but also meet the treatment needs in special environment (wartime, natural disasters, etc.).[1,2] The development and application of telesurgery robot has become a new trend around the world because it is helpful in solving the problem of trauma treatment and improving the local medical level in special area and special environment.

Development history of telesurgery robotic system

Due to the limitation of special regions and unbalanced development of medical technology, many patients lost the best opportunity for operation. The idea of telesurgery robot was proposed for the first time to quickly and safely treat trauma patients in the rear hospital in the wartime. With the development of medical and remote communication technology, the demand of telesurgery has increased. Laparoscopic and endoscopic technology changed the previous operation mode that operated under direct vision. By presenting the operation vision through video images, tele-present surgery came into reality, and it was early used for remote surgery guidance and education of complex operation and emergency trauma cases. In 1992, Satava and Green[3] first described the use of SRI International (Menlo Park, California, USA) remote operation system to directly control the movement of the mechanical tip to complete a part of the operation, which was the beginning of telesurgery robot and the turning point from tele-present to tele-operated surgery. In the same year, ROBODOC (Integrated Surgical System, Davis, California, USA)[4] was first proposed for orthopaedic trauma, aiming to improve the prognosis of cementless total hip arthroplasty by reducing technical errors. In 1997, Himpens[5] from Belgium completed the first long-distance surgical cholecystectomy using the tele-operated surgery system developed by the Intuitive Surgical Inc (Menlo Park, USA). In 1998, Carpentier[6] from France completed more than 150 long-distance robotic heart operations in one year. In 2001, American surgeons completed the world's first robot-assisted laparoscopic cholecystectomy using Zeus computer motion.[7] In 2009, based on Da Vinci system,[8] the US military proposed to develop a complete set of surgical robot system (trauma POD) in response to wartime environment, including surgical robot system, management and display system, control and supervision system, monitoring system, hand washing nurse robot system, device replacement system, device delivery system, and drug supply system, to realize the "unmanned" treatment mode. Although the system has not been in clinic, the research of the system indicates that telemedicine would enter the era of complete telesurgery in an "unmanned" mode.

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Construction of control platform for telesurgery robotic system

In order to achieve the function of remote control, it is necessary to build a telesurgery control platform, which mainly includes teleoperation system, communication system and telepresence system.

Teleoperation system

Teleoperation system is the core technology of telesurgery robot, which is controlled by the operator by sending the position command while receiving visual and other sensory feedbacks information, so that the slave manipulator can follow the action command of the master manipulator to operate.[9,10] The construction of the remote operating system mainly includes master manipulator, slave manipulator, servo system, processor and server. The master and slave manipulators mainly function to control and operate the robot respectively. The servo system is used to make the output controlled quantity of the slave manipulator move with the input target of the master manipulator. The server software mainly realizes the collection of analog signals and terminal position coordinates of the main operator, and it also has the functions of data processing, information coding, data transmission and reception, etc. The processor is mainly responsible for the calculation, communication and management of the whole control process. The construction of the teleoperation system is developed from the improvement of the original surgical robot system. Hannaford[11] described that Raven-II surgical robot system (Actual Surgical Inc., USA) was based on Raven-I by adding robot assisted operating system (ROS), changing the original servo system to the standard Linux kernel operating system environment, and improving the remote integration ability of surgical robot. The success of telerobot surgery requires better response and higher completion depending on the effective interaction between the operator and the operating system to simplify the operative process. It will be a new challenge for the realization of autonomous telerobot in the future.

Communication system

The communication system is the “medium” of the master-slave operating system and the image audio feedback system, where transmission speed and stability directly determine the safety and real-time of the telerobot surgery. Therefore, the choice of communication protocol and mode is very important. The Transmission Control Protocol/Internet Protocol, which is more reliable than User Data Protocol and is more suitable to transmit a large amount of data, is usually adopted to the transmission of control information.[12] Although the transmission speed is relatively slow, the time consumed by the controller in verification and error correction is greatly saved because of its transmission stability. In addition, adaptive Hypertext Transfer Protocol streaming and Real-time Transfer Protocol are chosen for the communication protocols of video and audio. In the past, satellite communication, optical fiber special line communication and Internet communication were commonly used.[13] Satellite communication has wide communication range, high reliability, and is unaffected by the geographical environment and bad weather; however, the transmission delay is long, which is about 0.125s (one-way), and the amount of satellite relay data is limited, which may affect the safety and stability of the operation. Fiber optic special line communication has the characteristics of low delay and high stability but high cost. The first long-distance robot-assisted cholecystectomy as mentioned above realized transatlantic communication via fiber optic special line. At that time, the total signal transmission delay was about 155 ms on average. Normal commercial Internet communication costs less and has low delay, but its stability and security cannot be guaranteed. Butner[14] put forward the 330 ms delay limit of telesurgery; however, with the increasing requirements for the complexity and safety of telesurgery, the standard has not been used in clinic. With the priority application of 5G communication technology in the medical field, it can effectively solve the problem of data transmission with the characteristics of high speed and low delay. In December 2018, Liu[15] reported the pig liver resection operation using the KangDuo telerobot (Kangduo Robot Co., Ltd., China) with 5G communication technology. The average delay from the moving the execution instruction to the end of the robot arm was less than 150 ms, but the large change in the speed of the master manipulation would lead to the decrease of the motion precision of the slave manipulator. The issue of transmission rate and delay can be better solved by 5G communication technology, but the security and the integrity of operation video image transmission need more practice in the future.

Telepresence system

The main function of the telepresence system is presenting the information concerning the vision of the surgical field and the surgical environment to the operator in an image-audio manner, thereby generating the feeling of presence.[16] Typical robot telepresence system includes light source, digital image, audio acquisition and processing system, intelligent decision-making and control execution system. The telepresence system has evolved from the initial simple function of image-audio acquisition and processing into a set of image-audio information that integrates the vision of the surgical field and the surgical environment and other images, with certain learning and adaptive abilities as well; it is now in the direction of intraoperative images with 3D patient-specific models, and combining with Virtual/Augmented Reality imaging. Klapan[17] proposed the application of 3D anatomical imaging technology to the telesurgery of nose and paranasal sinuses. Kim[18] introduced the tele-robot surgery with 3D imaging of the operating room. In the future, more high-speed image processing chips may be used for telesurgery robotic system with artificial intelligence and learning ability. Therefore, the biggest challenge of telepresence system at present is not to compromise the optimal balance of remote operation process due to excessive occupancy of available bandwidth when meeting the quality requirement of real-time medical image and video.

Clinical application of various types of telesurgery robotic system

Classification and clinical application of telesurgery robotic system

The telesurgery robotic system is mainly divided into short-distance telesurgery robotic system, which refers to master system and slave system in the same room, and long-distance telesurgery robotic system according to the transmission distance classification. According to the operation method, it can be divided into open surgery robot and interventional surgery robot, and further divided into general surgery robot, endovascular interventional surgery robot, neurosurgery robot, orthopaedic surgery robot, otolaryngology interventional robot system according to the application field. This paper mainly introduces the clinical application of different types of telesurgery robots according to the classification of the application fields.

Endoscopic telesurgery robot

Compared with other telesurgery robots, the development of endoscopic telesurgery robot was earlier and more mature. The first remote interventional robot-assisted surgery was a laparoscopic cholecystectomy operated by Zeus Surgical Assisted Robotic System (Computer Motion, USA). In 1999, the Da Vinci surgical robot developed by Intuitive Surgical Company of the United States could be applied to a variety of surgical interventions, such as general, thoracic, cardiac, colorectal, gynecology, urological, etc. It was the most widely used surgical robot system in clinical practice and the largest number of operations. Although from the current clinical application, Da Vinci still belongs to a short-distance telesurgery robotic system, it is also suitable for long-distance surgery in theory by its procedure control and remote guidance function. There are other common endoscopy telesurgery robots, such as Raven II system,[19] Lapabot system,[20] etc.

Neurosurgical telesurgery robot

The first neurosurgical telesurgery robot approved by the US FDA in the world was Socrates Robot Remote Cooperative System,[21] whose main function is to realize robot remote guidance, aims to improve the level of surgical care and surgical operation training. Another neurosurgical telesurgery robotic system named NeuroArm can fuse patient MRI images with 3D force sensors and integrate high-definition stereomicroscopy, but it is only used in short-distance surgery, and the problem of delay in long-distance surgery remains a challenge in the future.[22,23] In 2003, the fourth generation telemedical surgical robotic system (CRAS, China), developed by Beijing University of Aeronautics and Astronautics, completed the world's first telerobotic-directed neurosurgery. The 5th generation, which was strengthened the automatic positioning function, realized visual automatic positioning and reduced operation error, was successfully completed 2 stereotactic operations between Beijing and Yan'an through the Internet in 2005.[24]

Orthopaedic telesurgery robot

Although there are many well-known orthopaedic robotic systems abroad (including Robodoc from Curexo, USA; R10 from Mako Surgical, USA; Renaissance from Mazor, Israel),[25–28] there are few reports on their early application in telerobot surgery. Wang[29] from China reported in 2006 that several remote tibial fracture closed reduction and internal fixation with locking intramedullary nail operations were performed with the orthopaedic telesurgery robotic system (CRAS) developed by Beijing University of Aeronautics and Astronautics.

Endovascular interventional telesurgery robot

Endovascular interventional robotic system started relatively late. At present, several systems are known, such as the Senei X1 system[30,31](Hansen Company, USA) for coronary intervention, Magellan robotic system which was based on Senei X1 system for peripheral vascular diseases, the CorPath robotic system (Corindus Company, USA), and the R-ONE vascular robotic system (RoboPath Company, France).[32,33] In 2005, Beyar[34] proposed the concept and design of remote coronary intervention surgery, and reported for the first time that remote navigation system was used to successfully perform coronary stent implantation by controlling the NaviCath robot, achieving accurate guide wire navigation and device positioning. Endovascular interventional telesurgery robotic system in China is still in the experimental stage. Moreover, at present, endovascular intervention telesurgery robots are mostly limited to the surgical treatment of cardiovascular diseases, and only suitable for special guide wires and catheters, which are unable to complete multiple instruments and complex surgical operations.

Application of telesurgery robot in trauma treatment

As mentioned above, telesurgery robots can break through the restrictions of special region such as natural disaster areas, war zones, epidemic areas, etc, and perform telerobot surgery on patients under backward medical conditions, poor medical environment and shortage of medical staff in front. The significance of telesurgery robots in trauma treatment is that in emergency situations when emergency surgery can be performed in time without the need for evacuation transfer of patients. The trauma first aid of telesurgery robots can shorten the effective treatment time of emergency patients, improve the efficiency of treatment, and improve the prognosis of trauma patients under special conditions. Therefore, especially in the military field, there is an increasingly urgent need for telesurgery robots. As the concept of a semi-automatic telesurgery robotic TraumaPod[8] was proposed, it was demonstrated that surgeons could perform intestinal anastomosis and shunting in large vessels through long-distance surgery, and this process could support intraoperative CT scanning. McKee[35] reported that in the case of mass shooting, many bleeding patients lost their lives due to untimely treatment because the hostile environment prevented emergency personnel from reaching the victim safely. Emergency personnel could have taken simple life-saving measures to avoid many deaths. Thus, it was proposed to use telesurgery robot which was equipped with bomb handling robot (Wolverine, Northrop Grumman Remotec, USA) and wound forceps (IT Clamp, innovative trauma care) to demonstrate robotic wound clamping and alternative bleeding control.

Although few reports on the application of telesurgery robots in emergency trauma treatment were reported, there have been successful cases of telesurgery robots in trauma treatment, especially in orthopaedic trauma treatment. Karthik[36] reported that total knee arthroplasty and pedicle screw implantation using a surgical robotic system were as safe and effective as manual surgery in the treatment of joint and spinal trauma. The use of the Da Vinci system was also reported to assist in identifying anatomy and initial neurological repair during brachial plexus surgery.[37,38]

Current application limitations of telesurgery robot

Investment and operating cost

At present, the price of telesurgery robots on the market is expensive, such as commercial Renaissance Guidance system of about $500,000 each, Da Vinci robot of about $1.5 million each. Due to the special sterility requirements of surgical robots, the cost of one-time replacement of consumables is also high, coupled with the maintenance and repair costs of robotic systems, resulting in imbalances in investment and return, which is difficult for general hospitals to popularize. On the other hand, telesurgery robot has higher requirements for fast communication rate and low delay time, so the configuration of corresponding communication equipment and the use of transmission media require higher costs.

Ethical and legal issues

The liability caused by medical damage from telesurgery robots is a new problem beyond the traditional system of medical damage liability rules. As the robot can not only accept remote control to complete the operation, a telerobot surgery must be completed by multiple units cooperation at the same time. In case of medical errors, there is no relevant legal and ethical support for the determination of the responsible party including the control doctor, slave assistant surgeon, robot company.

Stability and safety

The stability and safety of telesurgery robots play a vital role in the success of remote surgery. Emergencies occurring in robotic surgery are more complex than those occurring in manual surgery. Depending on the type of emergency, the surgeon can decide to change the surgical approach or other solution, but additional instruments and supplies may be required in telerobot surgery.[39,40] In addition, the issues of network delay and the invasiveness of surgical procedures remain challenges in the future.

Telesurgery robot has a significant impact on the development and popularization of telemedicine in the future. The teleoperation, communication and telepresence system of telesurgery robots need interdisciplinary and multi-field technology development to meet different clinical needs. Telesurgery robots have been widely used in many medical fields, more advanced medical, communication, and engineering technologies are still needed to meet different challenges.

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Ethical statement

Not applicably.

Declaration of competing interest

The authors declared no competing interest.

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