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Remote orthopedic robotic surgery: make fracture treatment no longer limited by geography

Junqiang Wang [a], Jinqi Li [a], Yu Wang [b], Mehran Armand [c], Xieyuan Jiang [a,*]

[a] Department of Traumatology, Beijing Jishuitan Hospital, Beijing 100035, China
[b] Biomedical Engineering Advanced Innovation Center, Beihang University, Beijing 100191, China
[c] Applied Physics Laboratory, The Johns Hopkins University, Laurel 21218, USA

Although manufacturing and warehousing have benefited longer-term use of robotic technology to enhance respective industries, healthcare, particularly orthopedic surgery, has been slower to adopt robotic technologies. However, with tremendous recent growth, the field of robotics is now hitting an inflection point in healthcare generally, as well as telesurgery and telemedicine of orthopedics in particular.

The orthopedic surgery robot is a high-tech medical device that integrates basic and clinical medicine, ergonomics, mechanical and electrical engineering, and computer science. Since the beginning of the 21st century, the use of robotic systems in surgery has significantly increased, and general surgery, urology, gynecology, and the like, have come to the forefront of minimally invasive robotic surgery with the help of lumpectomy robotic systems [1]. However, orthopedic surgeons are still drilling nails, putting on plates, replacing joints, and performing minimally invasive endoscopic surgery with free hand. Compared with decades ago, the difference mainly lies in the advancement of models for nails, plates, and joint prostheses and the procedures of minimally invasive surgeries. For a long time, there have been only minor advances and changes in joint replacement procedures, concepts, materials, and instrumentation, without revolutionary changes. Orthopedic surgery robots were not developed until artificial intelligence (AI) emerged, indicating the beginning of a new era of intelligent orthopedics.

After more than 30 years of development, several surgical robots have been developed for commercial use worldwide, covering the fields of spinal surgery, joint surgery, orthopedic trauma, and so on. Foreign companies laying out the orthopedic surgery robot track include Stryker, Medtronic, Johnson & Johnson, Zimmer Bomber, and Smith & Nephew. Companies in China started late in this area but have made rapid progress in recent years (such as Tinavi Medical Technologies Co., Ltd., Beijing Hehuarebo Technology Co., Ltd., MicroPort, Weigao Group Co., Ltd., and Rossum Robot).

The orthopedic surgery robot can significantly reduce the fatigue level of doctors, reduce the number and time of intraoperative fluoroscopy, reduce the radiation dose to both doctors and patients, and improve the accuracy and precision of operating instruments, among other advantages [2]. Surgical robots are a vital tool for achieving precision medicine, especially for promoting medical homogenization. With robotic assistance, hospitals and doctors of different levels can achieve homogeneous treatment results. General surgeons can do more challenging and complex surgeries; experienced surgeons can make the results more precise, safer, and less laborious with the help of robots.

Currently available medical robots generally fall into three categories: supervisory controlled, telesurgical, and shared control. Supervisory controlled robots allow the surgeon to plan the operation in its entirety preoperatively; the robot then operates under close supervision by the surgeon. Telesurgical robots allow the surgeon to remotely control the robot and its instruments throughout the entire procedure. Finally, most orthopedic surgery robots are share-controlled, allowing the surgeon and robot to control instruments and motions [3].

The most difficult surgical operation in traumatic orthopedics is the closed reduction of pelvic fractures. The development of pelvic fracture reduction robots has been conducted in the United States, Japan, and Germany, but none has entered clinical application thus far.

Based on previous research, Beijing Jishuitan Hospital independently designed and developed new algorithms to apply the robot to the reduction of pelvic fractures and completed the development of the world's first intelligent fracture reduction robot. By the end of October 2022, the intelligent pelvic fracture reduction robot had completed 40 research clinical trials and 39 registered clinical trials in Beijing Jishuitan Hospital, indicating that the technical strength of orthopedic surgery robots in China has reached the international leading level.

Traditional pelvic fracture reduction surgery mainly relies on the surgeon's experience. Besides being time-consuming and labor-intensive, closed reduction by the operator with the assistance of multiple tractions is difficult to guarantee the accuracy of reduction. Accurate localization and complex three-dimensional (3D) reduction paths are necessary for pelvic fracture reduction. The orthopedic robot provides real-time monitoring of the entire process through intraoperative image alignment technology. The

* Corresponding author.
E-mail address: jxytrauma@163.com (X. Jiang).

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vision-based intelligent fracture reduction robot system consists of four parts: pelvic fracture reduction software (reduction planning software and intraoperative navigation alignment software), reduction robot, pelvic grip device, and optical tracking device. The healthy-side grip system consists of two nine-degree-of-freedom electronically controlled passive arms for stable control of the healthy-side pelvis. The optical tracking tool is connected to the pelvis and robot for real-time tracking during the operation. The system also includes a preoperatively calibrated navigation drill with optical tracking markers, which allows for real-time acquisition of the Schanz needle axial direction and tip position through the optical positioning device (Fig. 1).

The intelligent pelvic fracture reduction robot completely overturns the traditional "end-to-end" reduction concept, and the robot system will intelligently plan the best fracture reduction position using the preoperative 3D computed tomography reconstruction. During the operation, the robot can accurately and safely complete automatic pelvic fracture reduction with real-time 3D navigation and force position synergy. The notable changes include the following: from the need for doctors to make a surgical plan to AI automatic surgical plan; from static 3D navigation to real-time dynamic 3D navigation; and from simple position navigation to force position synergy control and automatic reduction. Thus, the orthopedic surgery robot is gradually evolving into the first assistant that physicians expect [4].

Robotic remote medicine is a new medical model that uses telecommunication networks as information transfer carriers. It integrates robotics, virtual reality, medical sensors, and AI technologies for clinical use, rapidly projecting superior medical resources, innovating graded treatment paths, improving the efficiency and quality of remote treatment, and accelerating the homogenization development of treatment services. There are three main forms of remote diagnosis and treatment: remote guidance, remote monitoring, and remote operation [5].

Several landmark robotic telemedicine cases have been completed globally since the beginning of this century. The 2001 "Lindbergh operation" allowed doctors in New York to perform a gallbladder removal surgery in Strasbourg, France, by controlling a "Zeus" robot via a private network [6]. Considering the cost of the network, China has focused on internet-based robotic remote clinical trials. For example, the Navy General Hospital led the first robot-assisted remote brain surgery (Beijing-Shenyang, 2003), and Beijing Jishuitan Hospital led the first robot-assisted remote orthopedic surgery (Beijing-Yan'an, 2006).

In 2007, Nguan et al. [7] performed 18 pyeloplasty procedures using real-time, internet protocol virtual private network, and satellite network connection (six of each). Network and objective operative data were collected. Despite network delays and jitter, it was feasible to perform the pyeloplasty procedure without significant detriment in operative time or surgical results compared with real-time surgery. In December 2012, Beihang University, in cooperation with the General Naval Hospital Hospital, completed the first remote offshore surgery in China.

Although China's telesurgery research started later compared with developed countries/regions, such as the United States and Europe, it has developed rapidly and has explored a model suitable for China's national conditions.

The abovementioned cases and subsequent clinical practice have shown that robots have unique advantages in remote surgery and a promising development. However, the high cost of private

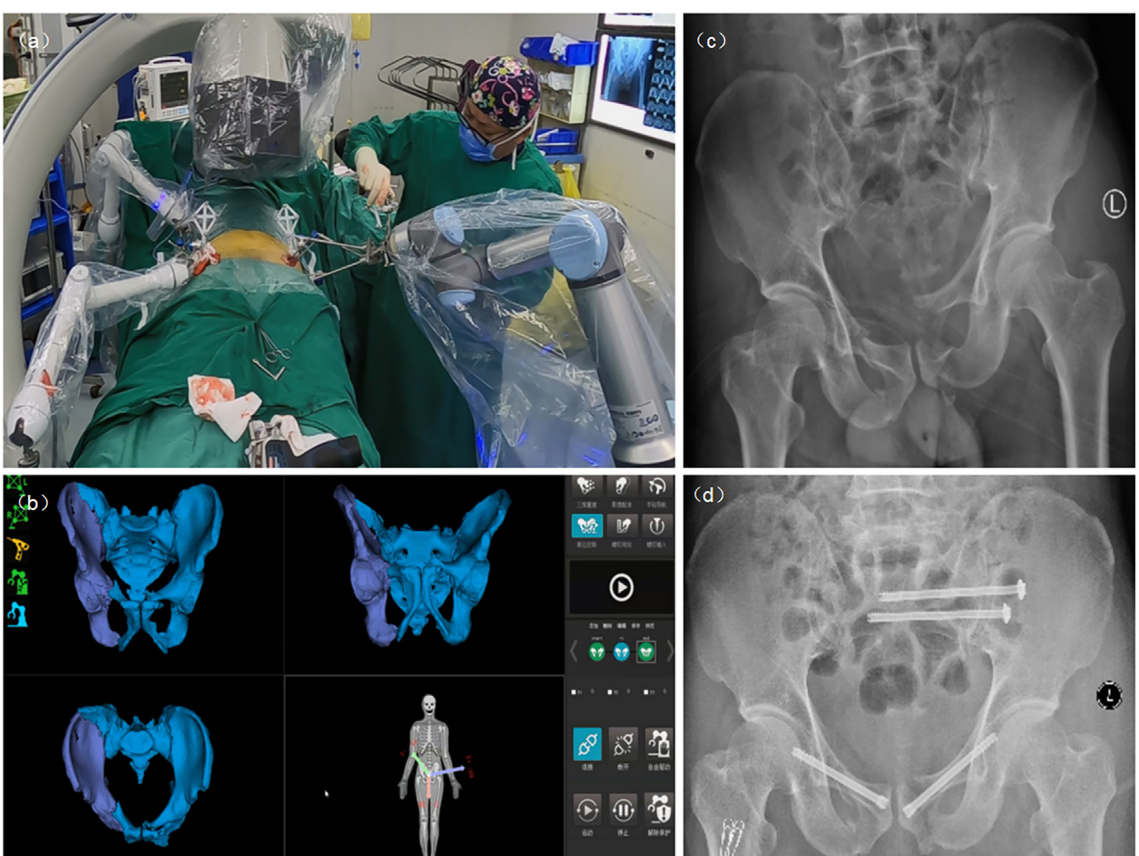

Fig. 1. A typical case: pelvic facture reducted by the intelligent pelvic fracture reduction robot. (a) The pelvic fracture reduction robot developed by Beijing Jishuitan Hospital automatically reducted fractures according to the planning procedure of the fracture reduction software. (b) Visual human–machine interface for intraoperative planning of a pelvic fracture reduction robot. (c) Preoperative X-ray of pelvic fracture. (d) Postoperative X-ray after robotic reduction of pelvic fracture.

networks and the instability and insecurity of traditional internet have largely restricted the popularization and application of robotic telemedicine.

With the advent of 5G technology, orthopedic surgical robots are entering a new direction—remote surgery. 5G technology supports telesurgery with high speed, latency below milliseconds, and high bandwidth, greatly increasing the accuracy and stability of remote surgery. The popularity of remote surgery has become technically possible, providing technical support for doctors to operate off-site and enabling quality medical resources to radiate to a wider area [8].

Since 2019, many foreign studies have been attempting to apply 5G networks to remote surgery and have gotten satisfactory results. Lacy et al. [9] applied the 5G network for remote surgical coaching of young doctors on the patient side. Based on this study, Acemoglu et al. [10] reported that their team applied a 5G network to perform robotic vocal cord surgery on a cadaver in an autopsy lab 15 km away, and the surgery was completed with an average network latency of 140 ms. This study shows that the low latency and high bandwidth features of the 5G network are key technologies for remote surgery, which can be used as a future network development direction for remote surgery. In March 2019, the General Hospital of the Chinese People's Liberation Army completed the world's first 5G remote-controlled craniocerebral surgery. A doctor in Sanya performed remote Parkinson's "brain pacemaker" implantation surgery on a patient in Beijing through a remote-controlled robot, which is an important step for Chinese 5G telesurgery to the world and an important guiding significance for the development of domestic remote surgery.

Approximately 700 units of the Mako arthroplasty robot have been installed worldwide, with 6 units installed in medical institutions, such as the Chinese People's Liberation Army General Hospital and the Peking University People's Hospital, mainly for total hip arthroplasty, total knee arthroplasty, and unicompartmental knee arthroplasty.

In recent years, Chinese orthopedic robots have entered remote clinics (e.g., TIROBOT, The "Skywalker" Robot, and Jianjia Robot), and Beijing Jishuitan Hospital has made outstanding achievements. Based on the TIROBOT, Beijing Jishuitan Hospital proposed a "one-to-many" 5G remote spine robotic surgery model and performed various orthopedic clinical demonstration surgeries. In 2019, several clinical surgeries were completed between Beijing and Yantai, Jiaxing, Tianjin, Zhangjiakou, and Karamay, verifying the clinical feasibility and scalability of "remote planning" technology and 5G remote robotic surgery. In 2020, the first 5G remote robotic-assisted trauma surgery (closed reduction and internal fixation of calcaneus fracture with screws) was performed in Suzhou, China. In 2021, at the Shanghai Ninth People's Hospital, the "Skywalker" robot was applied to complete a "one-two" 5G robotic remote knee arthroplasty surgery for two patients in Huizhou and Kunming. In September 2022, at the Beijing Jishuitan Hospital, the TIROBOT was performed to complete a remote knee arthroplasty surgery for a patient in Hangzhou. By the end of October 2022, Beijing Jishuitan Hospital has completed 180 orthopedic robotic 5G remote surgeries in 23 hospitals across 15 provincial administrative regions (19 cities), including 111 cases of spine surgery, 66 cases of traumatic orthopedic surgery, 2 cases of hand surgery, and 1 case of orthopedic surgery. Surgical path planning is a necessary step for robot-assisted operation in orthopedic surgery. The existing orthopedic surgical paths can be summarized into two categories: simple linear paths (mostly seen in pedicle screws implanting) and spatial complex paths (mostly seen in complex pelvic reduction, joint replacement, and laminectomy). The automation of these path-planning processes with the help of AI can not only significantly improve the efficiency of path planning but also ensure the standardization of paths without significant differences from one physician to another. From the perspective of the remote operation process, the orthopedic surgery process is usually long, and virtual reality to establish an immersive operation environment can effectively improve the clinical performance of doctors [11].

The robot telemedicine mode continues to innovate, from the existing "one-to-one" master–slave single-point remote control to the development of "one-to-many" and "many-to-one" networked collaborative mode, which not only enables a clinical expert to carry out simultaneous remote treatment of different patients (multiple locations) but also enables experts from different fields (multiple locations) to collaborate in the treatment of the same patient. The application scenario expands from conventional remote clinical to public health remote treatment services. (e.g., telemedicine and remote ward rounds of doctors during the coronavirus disease 2019 pandemic and sudden medical emergency rescue; remote emergency response to disasters, battlefield zones, and space). Due to the unbalanced distribution of medical resources in China, cross-regional consultation is common, which increases the difficulty and cost of medical treatment. Moreover, the trend of unreasonable patient treatment flow also makes the technical level of primary medical institutions decline, and the medical advantages of large hospitals are not utilized enough, which invariably wastes medical resources [12]. Especially for common diseases like fractures, telemedicine and remote robot surgery can make full use of reasonable medical resources to solve the problem of difficult and expensive treatment for patients [13].

Despite all the revolutionary breakthroughs in orthopedic robotic telesurgery, many experts in communication and medicine remain cautious about telesurgery. For example, if we rely too much on 5G telesurgery, patient life safety will be threatened if there are problems during the process. However, prematurely promoting scenarios that require particularly high timeliness and technology costs will lead to increased doctor–patient conflicts and more doctor–patient disputes [14]. Aimed to solve the above problem, China is building a 5G remote orthopedic surgery robot application demonstration scenario to explore an economical, effective, and safe orthopedic surgery robot telemedicine model.

The orthopedic surgery robot market in the world will grow even faster. In addition, to face clinical demands, the capacity of independent innovation must be further enhanced, the admittance environment of the market should be further optimized, the policies support of orthopedic surgery robots should be strengthened, and the research and development of key components should be accelerated, to promote the leapfrogging development of orthopedic robot industry and upgrade the manufacturing industry to a higher end in the value chain.

Another hot topic in orthopedic surgical robotic telesurgery is the data-driven role. Surgical data science [15] and real-world data have entered the field of robotic treatment and are entering the orthopedic surgery robotic telesurgery process. Solving the problems of effective remote surgery big data mining, efficient and safe transmission, and ethics of telesurgery is necessary to promot the standardized and long-lasting development of robotic telesurgery [13–15].

The development of orthopedic robotic telesurgery also faces many challenges. The remote surgery system needs further improvement. There is still a gap between the maturity of telesurgery products and clinical expectations. There is still a lack of a scientific and reasonable telesurgery evaluation index system [16]. It is still necessary to strengthen the training and talent cultivation of remote surgery teams to expand the depth and breadth of telemedicine applications. Orthopedic robotic telesurgery takes a qualitative leap and will certainly have a good prospect in the future, although its advantages are not so prominent at the current stage.

Conflict of interest

The authors declare that they have no conflict of interest.

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Junqiang Wang is a professor at Peking University, Chief Physician of the Orthopedics & Trauma Department, and director of the Intelligent Orthopedics Research Program at Beijing Jishuitan Hospital. He received his Ph.D. degree in 2018. His research interest is the diagnosis and treatment of extremity and pelvic fractures.

Xieyuan Jiang is a professor at Peking University, the director of Beijing Jishuitan Hospital, president of Beijing Institute of Traumatic Orthopedics. His research interest includes the diagnosis and treatment of limb bone and joint injuries and pelvic and acetabular injuries.