Application of AI integrated semi-autonomous robotics in spine surgery: A review

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Abstract. Spine surgery is a high-risk surgery associated with high precision and accuracy. Artificial intelligence (AI) and semi-autonomous robotics can benefit the surgery. This paper explores the impact of AI and robotics on improving surgical precision, accuracy, and safety with details on preoperative planning, optimal screw placement, and intraoperative real-time monitoring. In addition, the potential of AI-driven simulation spaces for training and skill assessment was evaluated. Various AI models and robotic systems have improved surgical outcomes by providing precise guidance and reducing human error. This review aims to summarize the recent developments and highlight the challenges of AI and semi-autonomous robotics in spine surgery.

Keywords: Spinal surgery, Preoperative planning, Surgical simulation.

1. Introduction

Spinal surgery is one of the most challenging operations in medical field due to the requirement of high risk and precision. The success rate of the surgery is not only depending on the surgeon's skill level, but also associate with the accuracy and safety of the surgical process.

Integrating AI with semi-autonomous robotics in spine surgery enhances precision, safety, and efficiency by providing real-time feedback and guidance during procedures. AI algorithms help in precise planning and accurate placement of implants, while robotic systems reduce surgeon fatigue by handling repetitive tasks. Continuous monitoring by AI ensures patient safety and allows for adaptive adjustments during surgery, leading to improved outcomes and faster recovery times. This integration also supports training through realistic simulations, ultimately contributing to better overall surgical care [1].

D'Souza et al. discussed the history of spinal robotics and focused on analyzing currently available robotic systems, comparing them to conventional spine surgery in terms of accuracy and safety [2]. McKenzie et al. systematically discussed the benefits and outcome measures of robotic-assisted surgery from different areas, including accuracy, indications, and the surgical learning curve, by analyzing 34 pieces of literature [3]. Galbusera et al. introduced five applications of AI and its subsets of technologies related to spine research, and briefly discussed the ethical issues of AI in the medicine field [4]. Zhou et al. explored the use of AI in spinal surgery, emphasizing its role in standardizing diagnosis and treatment plans through clinical transformation platforms [5]. Rasouli et al. concisely analyzed and discussed the vast potential of AI in the field of spine surgery in both the research and clinical arenas [6].

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In recent years, existing medical robots have been widely used in certain surgical procedures. but research on their application in spine surgery is still insufficient, especially the combined application of artificial intelligence technology and semi-robots has not been fully explored. This review is to explore the application of AI and robotics systems in spinal surgery, with a focus on analysing their impact on surgical accuracy and safety. By summarizing and evaluating the research results and cases in recent years, show the latest progress and challenges in this field, and then discuss application.

2. Background on spine surgery

Spine surgery always faces the problem of precision and safety because the spinal nerves are located next to the vertebrae. A small deviation in the location of the perforation and screw implantation can cause serious complications or even paralyze the patient. Surgeons with the highest level of skill still make mistakes, so the entire surgical process requires more precise and reliable methods to improve the safety and effectiveness of spinal surgery.

Artificial intelligence and semi-autonomous robotics can provide solutions for preoperative planning and intraoperative decision of spine surgery. Artificial intelligence algorithms can analyze detailed preoperative imaging, suggest optimal screw trajectories and predict potential complications. During surgery, robotic systems can assist in executing these plans with high precision, reducing the likelihood of human error. The combination of artificial intelligence and robotics can help standardize surgery, minimize risk, achieve more predictable and reproducible results, improving overall surgical outcomes, and providing significant advantages over traditional techniques that rely solely on the manual skills of the surgeon.

3. Applications of AI and semi-robotics in spine surgery

3.1. Diagnosis and preoperative planning

The application of AI and robotics in spine surgery is a rapidly advancing field. ML is applied in diagnostic imaging of the spine to address various disorders [4]. AI and robotic technology can better help surgeon to analyze the position of the vertebral body, the degree of deformity, and the detection of tumors from the images, and to plan the route of the implant.

Suri et al. developed a deep learning neural network and trained it on MR, CT, and X-ray imaging data collected over a period of 15 years since 2005 to allow the system to quickly and automatically segment vertebrae to aid in radiomics studies and to gather information about underlying spinal diseases or diagnoses [7]. Fang et al. introduced a deep convolutional neural network for automatic vertebral localization and segmentation with the assessment of bone mineral density in CT images for early osteoporosis diagnosis [8]. Jamaludin et al. proposed a Convolutional Neural Network framework capable of automatically grading spinal lumbar MRIs radiologically and localizing predicted pathology hotspots with a potential application in other medical task require weak supervision [9]. Pal et al. combined random forest and fuzzy c-means algorithms to improve the accuracy of tumor type segmentation, classification, and localization in T2 MRI lumbar spine images for improved diagnosis planning and treatment outcomes [10]. Chu et al. presented a learning-based framework combining random forest regression and classification to fully automate the localization and segmentation of vertebral bodies from 3D CT and 3D T2-weighted TSE MR images with smaller average error [11]. Elsayed et al. provided a spatial computing (SC) case study that described how SC can assess graft size, trajectory planning, and psoas muscle position for critical neurovascular structures, improving surgical accuracy and limiting potential complications [12].

In addition to these basic diagnoses, most spinal surgeries require the placement of implants, and it becomes important to plan for the placement of implants prior to surgery. Wi et al. developed a simulator that provides 3D imaging and multiplanar reconstruction to assist with preoperative planning. Surgeons can directly select or modify the appropriate screw size and implant trajectory within the simulator, which helps less experienced doctors and aids in analyzing special cases [13]. Ma et al. developed an AI model called "Bone's Trajectory" to optimize pedicle screw trajectory planning, providing higher pull-out force to prevent screw loosening associated with osteoporosis. The model is also expected to be integrated into robotic surgical navigation systems [14].

The integration of AI and semi-autonomous robotics has already demonstrated improvements in preoperative planning. Machine learning algorithms is used for image segmentation, spine tumor detection, and surgical planning. There remain several challenges and limitations. For example, how to measure cumulative radiation dose to a patient during Preoperative CT image acquisition and alignment, ensuring the generalizability of AI systems across different clinical settings and imaging equipment.

3.2. *Optimal screw placement position and decision*

Implants are frequently used in spinal surgery. It is particularly important to select the appropriate screw, route of implantation and determine its accuracy and safety. AI and robotic technologies have shown remarkable progress in optimizing screw placement positions and surgical decision-making in spine surgery.

Jia et al. demonstrated that an AI model (Surgiplan AI) would outperform freehand selection in choosing screw length and diameter. The AI resulted 4-7 minutes faster in screw selection compared to manually and ensures the safety of the screw size parameters it chooses [15]. Lieberman et al. provided a complete surgical procedure using preoperative planning software and robotic guidance system for pedicle screw placement and conclude that it facilitated the feasibility and accuracy of the surgical plan and reduced the risk of catastrophic complications due to surgical complexity [16]. Fatima et al. confirmed the accuracy and safety of robotic pedicle screw placement through a meta-analysis. The results indicated that patients undergoing robot-assisted pedicle screw placement are more likely to achieve "perfect" accuracy compared to freehand methods. Additionally, the robot-assisted approach significantly reduces complication rates, intraoperative radiation exposure, and proximal facet joint violation compared to the traditional freehand technique [17].

Furthermore, real-time monitoring of screw placement accuracy during surgery plays a crucial role. Ahmed et al. provided the first detailed surgical procedure using real-time image-guided, robot-assisted spine surgery with a system called ExcelsisuGPS [18]. Jia et al. described that during real-time monitoring of screw placement accuracy, the AI model confirmed whether the selected screws lead to vertebral body breakage, and the AI results provided a quick reference for determining screw length and diameter [15]. Ao et al. proposed an intraoperative planning method for robotic spine surgery based on safe deep reinforcement learning (DRL). This method utilizes real-time observations for drilling path planning and trains the DRL agent using simulated surgical data to establish a foundation for future intraoperative decision-making [19].

The application of AI and robotic systems can provide accurate screw selection, real-time monitoring, and intraoperative planning. Questions like how can use AI to eliminate errors from image and equipment acquisition and registration. Also, there is uncertainty about if surgeons can follow standardized robotic surgery procedures to operative surgery. The standardization of robotic surgical procedures needs to be clarified.

3.3. *Simulation space for training and practice*

AI and robotic technologies provide a realistic virtual environment that surgeons can practice complex surgeries without the risks associated with real surgery. During a virtual simulation, AI can help surgeon develop their skills by using ML or other model to collect and analyze the data. Virtual practice is invaluable to both experienced surgeons and trainees as it increases their proficiency and confidence. In addition, these simulation systems can provide feedback to identify areas for improvement, thereby promoting continuous learning. Winkler-Schwartz et al. developed a checklist that provides a framework for the study of virtual reality surgical simulation and ML to bridge the knowledge gap between computer science and medicine and to facilitate the development of surgical education [20].

Abboudi et al. provided a systematic overview of several robotic surgery simulators available at the time, discussing the advantages and disadvantages of various platforms from different perspectives. They concluded that the combination of simulator and traditional training can be beneficial for the future training of robotic surgeons [21]. Lam et al. analyzed 66 studies related to the assessment of surgical technical skills using machine learning. Among these studies, 31 reported high accuracy in determining the performance of at least one task, highlighting the potential of ML-based surgical performance assessments and show that machine learning can accurately, reliably, and objectively track surgeon performance. The precise surgical performance assessment may be integrated into surgical training [22]. Mirchi et al. developed the Virtual Operative Assistant (VOA), an AI-driven tutoring system that provides learners with objective and automated feedback. This system integrates expertise classification, proficiency-based feedback, and instructor input into a cohesive learning framework [23]. Fazlollahi et al. compared remote expert guidance with the VOA tutoring system to determine which method better helps learners achieve higher performance in simulated training. They concluded that simulation surgery with feedback from the AI tutor was more effective than remote expert guidance [24]. Park et al. discussed the key facts of enhancing surgical simulation using AI-driven technologies. They summarized and discussed the current state of AI in surgical simulation and suggested future improvements in terms of technology, cost, and regulatory. According to their findings, the assessment of surgical skills using simulated tabletop tasks may not accurately reflect trainees' performance in operating room due to the complexity of real surgical environments [25].

Farah et al. evaluated the educational effectiveness of simulation-based models in resident spine surgery training and suggested enhancing simulator development to provide a list of intricate pathologies [26]. While many virtual environments effectively aid surgeons in training their surgical techniques, they are often not tailored for spinal surgery. AI algorithms still lack valid evaluation criteria to accurately assess participant performance. A large amount of surgical data is required to effectively train machine learning algorithms.

4. Summary

AI and robotics improve precision, accuracy, and safety in spine surgery. AI algorithms can analyze diagnostic images, predict complications, and optimize implant trajectories during preoperative planning. Robotic systems provide optimal screw placement and real-time feedback during surgery which is significantly reducing the risk of complications. In addition, simulations can allow surgeons to improve their skills in a risk-free environment. However, more data is required to evaluate the AI algorithms. The standardization of robotic surgery also needs to be clarified. Continued research and development are essential to solve these issues.

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