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Review of the Present and Future of Spinal Robotic Technologies: Far from navigation

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The spine's unique anatomical structure presents elevated challenges and risks in surgical procedures. Robot-assisted spinal surgeries developed rapidly in recent years. The robot-assisted techniques demonstrate promising outcomes, including the remarkable reliability, safety, efficacy, and decreased gamma exposure in spinal surgery, especially for the area of pedicle screw placement. The robot-assisted techniques are more and more popular all over the world, with the advantages like precision navigation and visualization, real-time feedback, and remote surgery. Despite significant achievements and promising prospects, the current clinical application of robot-assisted surgery remains relatively limited, with the navigation and pedicle screw insertion functions mostly used. This article reviews the current progress and outlines the future development direction in robot-assisted spine surgery.

Keywords: Robotics, Spine, pedicle screw placement, navigation.

INTRODUCTION

The unique anatomical structure of the spine significantly increases the difficulty and risk of surgery compared to other orthopedic procedures[1]. The efficacy and safety of spinal surgery often rely on the experience and on-the-spot performance of surgeons, as human reliability is influenced by multiple factors, including physical strength, emotional state, and professional expertise. Additionally, the prolonged exposure to radiation during spinal surgery over the years poses a certain challenge for surgeons[2].

To address these challenges, surgical robot has emerged. Since its introduction, robot has demonstrated excellent reliability, safety, and efficacy in spinal surgery. Particularly noteworthy is its performance in the insertion of pedicle screws, where robot surpasses the accuracy and safety of manual procedures[3,4]. However, despite the significant achievements and promising prospects, the current clinical application of robot-assisted surgery remains relatively limited, with areas such as laminectomy still requiring further exploration. This article reviews the current progress in robot-assisted spine surgery, and projected the future development direction of robot-assisted spinal surgery.

We reviewed literatures from Pubmed, ScienceDirect, Scopus and Google Scholar databases on articles between 1990 and 2023. The following key words were used: "spine", "robot", "navigation". All references were exported from the databases to a reference management tool.

1. Application of Robot-assisted spine surgery

The application of surgical robots in the field of spinal surgery has become an integral part of modern medical technology, providing surgeons with a more precise and stable operating platform, thereby enhancing surgical outcomes and patient recovery processes. Currently, the clinical applications of surgical robots in spinal surgery include the following aspects:

I. Precision Navigation and Visualization:

Spinal surgeries Surgical robot systems employ highly accurate navigation systems to monitor the patient's anatomical structures in real-time during surgery. And the systems are typically equipped with advanced imaging technologies, offering high-resolution three-dimensional images that allow surgeons to visualize the patient's spinal structures more clearly[5]. This facilitates surgical path planning, ensuring the accuracy of the procedures like locating and manipulating spinal structures. Furthermore, the precise localization techniques make the minimally invasive procedures possible, thus reducing the risks and injuries associated with surgery.

II. Robot-Assisted Pedicle Screw Fixation:

The close anatomical relationship between vertebral pedicles and associated neurovascular structures highlights the potential for serious morbidity resulting from surgical misplacement of pedicle screws. According to a geometric model representing spinal anatomy, it is suggested that to ensure successful screw implantation, a maximum translational error of under 1 mm and a rotational error of less than 5° are considered permissible[6]. In pedicle screw fixation procedures, surgical robots assist surgeons in precisely determining the position of pedicle and guiding the insertion of pedicle screws, thereby enhancing the accuracy and stability of the surgery. And various researches have reported promising outcomes in comparison with robot assisted technique and free hand technique, regarding with the pedicle screw placement accuracy rate[7,8].

III. Real-time Feedback during Surgery:

Surgical robot systems typically feature real-time feedback functions, allowing surgeons to receive crucial information such as visual sense, force, pressure, and tissue response during the surgical process. This helps surgeons better control the surgery, much easier and safer than free hand techniques[9].

IV. Remote Surgery:

Some advanced surgical robot systems support remote surgery, enabling experts to participate in surgeries from a distance. This holds potential benefits for training and collaboration, especially for those patients in underdeveloped area[10]. Wei Tian et. al reported 12 patients with spinal disorders treated with 5G telerobotic spinal surgery, and concluded with that 5G telerobotic spinal surgery is both efficacious and feasible for the management of spinal diseases with safety[11].

2. The current state of robot-assisted spine surgery: Just an advanced navigation system?

It is not accurate to label robot-assisted spine surgery as advanced navigation robots. While navigation is indeed a crucial feature, the application of robot-assisted spine surgery extends far beyond this aspect. Surgical robots represent a more complex and comprehensive system, integrating various advanced technologies to provide a more precise, safe, and effective surgical process. Here, we list several key distinctions between navigation robots and spinal surgical robots:

I. Navigation Accuracy:

Navigation robots primarily focus on precise positioning, whereas spinal surgical robots not only possess high-precision navigation capabilities but also incorporate advanced imaging technologies, real-time feedback systems, and precise manipulation methods. Also, the traditional surgery under navigation relays on the experience and feeling of the surgeon, the procedures are guided by the navigation, but in practice, the surgical maneuvers or path always deviate from the navigation guidance. On the contrary, the robot assisted surgery always guide the surgery with the application of mechanical arm, the surgeon can make the incision and place the screws easily and precisely. In fact, the robots can place the screws automatically, though the technique is not widely used considering the ethical issues[2,12].

II. Three-Dimensional Imaging and preoperative planning:

Spinal surgical robots are typically equipped with high-resolution three-dimensional imaging systems to offer clearer anatomical structure images, aiding surgeons in better planning the surgical path preoperatively[12]. In multi-segment surgeries, the free hand placement of pedicle screws often presents a challenge wherein the posterior ends of the screws are not consistently aligned in the same plane, thereby complicating the placement of the connecting rod. The incorporation of visual technology in robotic surgery facilitates preoperative planning, empowering surgeons to refine the entry points, angles, or depths of the screws to ensure uniform alignment of the posterior ends within the same plane. This refinement streamlines the rod insertion process, especially in cases involving spinal curvature.

III. Real-Time Feedback System:

Spinal surgical robots come with real-time feedback systems that monitor various parameters during the surgical process, including visual sense, force, pressure, and tissue response, helping surgeons better control the operation[9].

In summary, while navigation is a key component of spinal surgical robots, they represent a more comprehensive and complex system, integrating multiple technologies to provide a higher level of surgical precision and improved patient treatment outcomes. Therefore, simplifying their functionality and application scope by merely considering them as advanced navigation robots may oversimplify their capabilities.

3. Is the ability of spinal surgical robots limited to assisting pedicle screw placement?

Though the current crucial function of spinal robots is pedicle screw placement, the robot can do much more beyond it.

I. Precision Positioning and path planning in subchannel and endoscopic surgeries

An important procedure in subchannel and endoscopic surgery is the placement of the channel. For unexperienced surgeons, the procedure is always time-consuming and laborious. And sometimes, the inaccurate placement of the channel may bring a lot of inconvenience and even danger to the surgery. With the help of the robot, the surgeons can plan an optimal path preoperatively, make the incision precisely, and place the channel easily[13,14].

II. Minimally Invasive Surgery

With the assistance of surgical robots, doctors can achieve minimally invasive surgery, completing the procedure through small incisions, reducing tissue damage, postoperative pain, and promoting faster recovery.

III. The potential use of robot in spinal decompression surgery

Spinal decompression surgery constitutes a prevalent intervention directed at relieving pressure on neural structures within the spinal canal, frequently indicated for conditions such as spinal stenosis. The integration of surgical robots represents a significant stride in advancing the field of spinal decompression surgery. Weishi Li[15] conducted an initial inquiry into the utilization of a collaborative spine robot system in decompressive laminectomy. This system incorporates a 6-degree-of-freedom robotic arm, a force sensor, and a piezoelectric osteotome system. The findings of this investigation validate the safety of the innovative spinal robot system for laminectomy, albeit underscoring the imperative for further refinements to optimize its efficacy. Wei Tian proposed a multilevel fuzzy control strategy based on force information in robot-assisted decompressive laminectomy to augment the quality and dynamic performance of the robotic system during surgical procedures. The orchestrated grinding path is meticulously planned in medical images post 3D reconstruction, with alignment between the robot and images achieved through navigation registration[16]. Furthermore, a meticulous 3D model of the laminae derived from CT images is imperative for robot-assisted decompressive laminectomy. Hongjian Yu introduced a two-stage network, demonstrating superior performance relative to baseline models in laminae segmentation tasks, with reduced computational demands and learnable parameters. This approach enhances the precision of laminar models and diminishes image processing time, thereby contributing to a more meticulous planning trajectory and potentially advancing the clinical application of robot-assisted decompression laminectomy surgery[17]. Yuan Xue presented a k-nearest neighbors machine learning approach proficient in identifying three milling states based on vibration signals: cancellous bone, ventral cortical bone, and penetration in robot-assisted cervical laminectomy. This method serves to ensure the safety and efficacy of robot-assisted laminectomy procedures[18]. However, though lots of studies have been performed and promising results were reported, the robot assisted decompression surgeries are still far from clinic, more researches are needed.

IV. Cervical spine navigation and enabled robotics

The distinctive anatomy of the cervical spine underscores the significance of precision in surgical procedures to ensure the safety and efficacy of interventions. While the utilization of robots is particularly crucial for cervical spine procedures in comparison to the lumbar or thoracic spine, challenges arise due to the inherent mobility of the cervical spine during respiration, limiting the application of robot-assisted surgeries. Nevertheless, ongoing preclinical investigations have explored the potential utilization of robotic assistance in cervical spine surgeries. This exploration encompasses various aspects, including C1 lateral mass, odontoid fracture fixation, C2 pedicle, translaminar, subaxial lateral mass, mid-cervical pedicle, navigated decompression, ACDF cases, and associated techniques[19]. The field exhibits substantial potential for diverse applications.

V. Intelligent surgical planning

Artificial intelligence and machine learning can be integrated into the spinal robot. A personalized surgical planning is possible considering the unique anatomical structures and pathological conditions of each patient[20].

In summary, while pedicle screw fixation is a significant application of surgical robots in spinal surgery, their functionalities extend far beyond this.

They provide comprehensive support for various spine surgeries, complex anatomical operations, and overall optimization of the surgical process. Therefore, it can be said that pedicle screw fixation is a part of the functionality of surgical robots, but not their sole application.

CONCLUSION

Robotic technology in spinal surgery demonstrates significant clinical advantages. Currently, its applications are prominently seen in precise navigation and pedicle screw fixation with real-time feedback, thus providing a more stable and accurate surgical platform for enhanced patient outcomes. The future of spinal robotics holds potential for expanding into remote surgery, intelligent surgical planning, and a broader spectrum of spinal procedures like decompression and cervical procedures.

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