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Study of Application of Robotics in Spinal Surgery

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Abstract. Pedicle fixation during spinal surgery done with robot assistance has sparked a wave of contemporary discourse within the surgical field. This contrasts with conventional methods such as freehand with fluoroscopy assistance. The comparison between the novel and conventional techniques, the gradual application of robotics into spine surgical field, prospects, and limitations of applying robotics in spinal surgery will be discussed in this review. Spine surgery with robot assistance was shown to have lowered the risk of surgical spine in multiple aspects including radiation exposure, neurologic/vascular damage due to its high precision. The first established of robotics into the system which had pioneered the field and which subsequently led to more innovative technologies that target the conveniency, accuracy and duration for incorporating robots into spinal surgery procedure. With the acceleration of inventions and reduced intervals between their emergences, had drawn some attention to the learning curves associated with the application of robotics in spinal surgery. Albeit the many flaws being refined with robot assistance during spinal surgery, however, the effect as compared to other techniques is still not as prominent and impactful thus, leading to the slow progressing of incorporation into the spinal surgical field.

Keywords: Robotics In spinal surgery, conventional pedicle screw placement, fluoroscopy**,** learning curves.

1. Introduction

Application of robotics in spinal surgery has been a hot topic over the past decades. Many spinal surgeries require the use of pedicle screws for fixation and stabilization of the vertebra [1]. Pedicle screws have been in use since 1959 when Boucher first reported their role, and they gained prominence in the 1960s through the work of Roy Camille [2]. In conventional freehand techniques, surgeons identify regions for screw insertion using anatomical landmarks, which has been shown to be sufficiently accurate [1]. However, the risk of screw misplacement ranges from 2-31%, heavily depending on the experience and surgical skill of the surgeon [3]. Misplacement or mispositioning of pedicle screws can lead to nerve or vascular injuries, which can progress into severe complications [4]. The demand of enhanced accuracy in spinal surgery has led to the natural progression in the procedure for placing pedicle screws effectively. Understanding the complicated outcomes of pedicle screw misplacement helps physicians emphasize the importance of accuracy in robotics. New technology should fulfill several criteria, including quality, efficiency, and cost-effectiveness [5]. The major criterion of quality should be meet by spinal-robotics lies in its ability to mitigate inaccuracies and minimizing causing damage while aiding pedicle screw placement.' Furthermore, efficiency is typically a primary concern in all developments. Utilizing robotics to aid in pre-planning the trajectory that guides pedicle screw placement could significantly reduce surgery time, thereby maximizing productivity in a shorter period. Hence, few fundamental properties must be considered for the widespread adoption of robotic surgery, particularly from the perspective of healthcare providers: effectiveness and accuracy [2].

In 1985, robotics made its debut with the introduction of 200 Unimation PUMA (Programmable Universal Machine for Assembly) manufactured robots, which successfully conducted biopsies of intracranial lesions. Since then, robots have become increasingly prevalent in the field of neurosurgery, earning recognition from neurosurgeons. The application of robotics has expanded into various aspects of neurosurgery, including brain biopsies, neuroendovascular interventions, and spinal instrumentation [6].

While integrating robotics into spinal surgery sounds novel, it introduces a new learning curve for surgeons. This learning curves may entail unfamiliarity when it comes to handling the robotic systems potentially increases challenges in coordination and manipulation. This led to the risk of complications for the first few attempts in performing robot-assisted surgery. Therefore, addressing this aspect is crucial when researching its application in the field, as it could pose a limitation to the widespread acceptance of robot-assisted spinal surgery [7]. This review provides a brief overview of application of robotics in spinal surgery. It will cover various aspects, including spinal surgery comparison with and without robot application, types of robotics systems, and their impact and performance to date in healthcare systems.

2. Spinal surgery without robots application

Since the introduction of the pedicle screw placement method in 1959, pedicle screw placement has been widely used in spinal surgery for its multipurpose use, for example, stabilization, instrumentation, spinal fusion, and more [2]. The mathematical model of vertebrae has established the close anatomical relations of the spine and neurovasculature. It determines that the maximum deviation pedicle screw placements from their ideal position should not be more than 1mm horizontally and that the deviation of the rotation degree of the pedicle screw should be less than 5 mm [8]. Misplacement of the pedicle screw could lead to severe outcomes. Consequences such as neurovascular damage, penetration to adjacent visceral organs, and leakage of cerebrospinal fluid due to tearing of dura mater that could in turn form severe complications depend on the perforated structure [9].

Historically, placement of the pedicle screw without assistance from fluoroscopy or intraoperative image guidance resulted in a high rate of inaccuracy [10]. The free-hand technique to place the pedicle screw during spinal surgery heavily relies on anatomical landmarks and the surgeon's experience and skill. A pedicle screw is placed using anatomical landmarks and X-ray imaging, which helps surgeons assess the median alignment of the spine [2]. The pedicle screw spanned all three columns of the spine: the anterior, medial, and posterior columns. With this, it played a vital role in stabilizing the spine and helping with the healing process [11]. A pilot hole in the lumbar region was created at the junction of the pars articularis, superior articular process, and transverse process, while in the thoracic region it is at the center point of the triangular confluence of the superior articular facet, the transverse process, and the pars articularis [2].

The Gertzbein and Robbins grading system is used to grade the position of pedicle screw placement. It has categories A to E, and each corresponds to a different level of cortex violated by the pedicle screw. A is the perfect placement, and E is the worst violation.

Freehand techniques have a misplacement rate that ranges from 5% to 41% in the lumbar region and from 3% to 55% in the thoracic region [9]. Another study showed that 250 pedicle screws placed without assistance of fluoroscopy resulted in 4% breach of the pedicle of the vertebral cortex and were found more frequently in the thoracic pedicle (7 screws) than in the lumbar pedicle (4 screws) due to their smaller size and more complex morphology [2] [11].

To address this issue, the development of fluoroscopy-guided, computer-assisted navigation and robot-assisted spinal surgery was developed to induce greater accuracy. Although the addition of fluoroscopy has increased accuracy, the risk of nerve and vascular damage still persists [1]. Furthermore, the use of fluoroscopy reportedly increases the radiation exposure of surgeons and staff [1][10]. Details of robot-assisted spinal surgery will be discussed in the following paragraphs.

3. Robotic Application in Spinal Surgery

Spine surgery often demands sophisticated and detailed manipulation of vital structures through restricted surgical routes. Furthermore, the complicated and repetitive procedure often requires a substantial amount of time to complete. Thus, incorporating robots into spinal surgery could augment the limitations of human ability with its refinement to encounter addressed issues.

Surgical robots are categorized into three divisions: telesurgical systems, which allow surgeons to operate remotely completely; for example, the da Vinci surgical system. Telesurgery mitigates the few of the major issues such as shortage of surgeons, eliminates long-distance flight required for patience from rural regions, decreasing financial burden significantly and so on. Next up is a controlled system under supervision where the robot has full autonomy in operating while the surgeon is next to it, supervising it attentively. This is predominantly used in stereotactic surgery as it enhances the navigation and accuracy of microsurgery. Finally, in co-autonomy shared-control models in which the robots and surgeons both control the movement simultaneously, this category of robot is advantageous as it is equipped with haptic feedback, which stabilizes the hand tremors of the neurosurgeons [5] [6].

The development of robot-assisted spinal surgery can be seen on an increasing trajectory. Devices include Mazor systems (Medtronic), ExcelsiusGPS (Globus Medical), ROSA ONE Spine (Zimmer Biomet), TiRobot (Beijing Tinavi Medical Technologies Co., Ltd.), Cirq (Brainlab AG), and others, all of which are built to meet the demand of the market [7]. As a newly emerging field, numerous studies and research efforts have been conducted to ensure its safety and efficacy, particularly in clinical settings. Robotic guidance has been shown to have near-99% accuracy [12]. Another study found 94.5% accuracy with robot-assisted pedicle screw placement and 91.4% accuracy in the conventional way [13]. However, controversy arises as there are demonstrations of trials that have shown that robot assistance has the same accuracy or even less than freehand pedicle fixation [14]. Excluding the early randomized controlled trial in 2012, which discovered the decreasing precision of the SpineAssist® (Mazor Robotics, Caesareas, Israel) system, in most cases, robotic-assisted spinal surgery remains highly precise and effective with the measurement guidance of the Gertzbein-Robbins System (Grades A or B) ranging from 85% to 100% [14].

4. Types of spinal-robotics platforms

A few major robot systems in the current field are Mazor X Stealth Edition (previous models include the Mazor X, SpineAssist, and Renaissance; Mazor Robotics, Caesareas, Israel), Excel-SiusGPS (Globus Medical, Audubon, PA), and ROSA (Zimmer Biomet, Warsaw, IN) [1]. Since the first FDA-approved spinal robotic platform, SpineAssist (Mazor Robotics LTD., Caesarea, Israel), was released in America in 2004, robotics in spinal surgery has continuously evolved rapidly.

SpineAssist works by providing a frame with its arm having six degrees of freedom for its automatic alignment with the preplanned trajectory for which the neurosurgeon will be drilled manually through the established framework by the Hover-T frame with an extension bridge [15] [16]. However, several concerns emerged. Situations such as failing to merge pre-operative CT scan with intraoperative fluoroscopy, technical limitations of the robotic arm to meet the designated trajectories pre-planned by surgeons led to discrepancies [17]. Additionally, study had shown out of 960 screw placements, 11 placement were inaccurate indicating the possibilities of drill skiving [18]. Later on, Mazor Renaissance was substituted; several features, such as its drill bits and pattern recognition algorithms, were enhanced. Furthermore, there was an expansion of clinical applications [16, 17]. Although improvements have been made, the accuracy rates of both models range between 85% and 100%, as possible misplaced pedicle screws due to errors resulting from drill skiving persist [16]. The third generation being approved by the FDA in 2016, the Mazor X, fixed the few issues mentioned in the previous two models [16]. It does this by enabling the robotic arms to be attached to the operating table and by integrating the navigation system for real-time imaging of the geometry of the spine and avoiding intraoperative collisions with the integration of a linear 3D visual tracking camera [6] [16] [17]. However, the requirement of placing pins for the intraoperative CT scan could possibly be placed wrongly if the pin is not driven correctly into the PSIS (posterior superior iliac spine), especially if the patient is obese. Furthermore, the use of CT scans still exposes patients and healthcare workers to radiation [8]. Finally, the latest conversion was publicized by Mazor Robotics shortly before it was sold to Medtronic (Medtronic, Memphis, TN, USA). The Mazor X Stealth was approved by the FDA in November of 2018 [15]. The conversion of Mazor X to Mazor X Stealth consists of the major additional features known as Medtronic's Stealth surgical navigation software. Integration of this reduces the involvement of manually conducting surgery through refinement of the navigation system, better trajectory planning, and so on [14].

ROSA (Zimmer Biomet, Warsaw, IN) has its first model manufactured for operation on the brain. The emergence of ROSA Spine, which was approved in 2016, targets playing a role in spine surgery. The ROSA spine consists of one robotic arm and one with an optic camera [17]. It is gaining market share in the surgical field with its equipped 3D camera, which primarily focusing on enhancing the accuracy of pedicle screw placement [6]. ROSA spine operates using intraoperative fluoroscopy or intraoperative CT scan for navigation purposes while the surgeon places the pedicle screw [6][14]. In 2019, the ROSA ONE system was approved by the FDA. It is a unique combination of ROSA knees and the ROSA ONE brain system, becoming the only robotic platform capable of attending to diseases arising from the spine, knees, and brain together. Greatly improve the cost-effectiveness [14]. In the ROSA ONE system, several enhancements were made to its predecessor's basic features, including an improved navigation system and a 6-degree free range of movement, thus increasing its flexibility [6]. A study has shown the ROSA ONE application benefits the patient by reducing the possibility of developing complications and reducing blood loss [6].

The Excelsius GPS was approved by the FDA in 2017. Different from the previous Mazor system, in which all models were fixed to the bone, Excelsius GPS is mounted on the floor [14]. It is also the first FDA-approved platform that does not require Kirshner wire, which is a tool to help stabilize the spine by mounting a frame on the patient [6]. Instead, the pedicle screw could be placed via its rigid robotic arm, which reduces the risk of paraplegia caused by the migration of Kirschner wires during operation [6][14]. Furthermore, similar to ROSA and the last two Mazor models, Excelsius GPS does not require a preoperative CT scan, thus contributing to the decrease in radiation exposure [6]. The incorporation of the surveillance marker QuattoTM spike that is separated from the reference base acts as a fixed point for navigation references for guiding the navigation. Moreover, Excelsius GPS has a shock-absorbing reference base that aids in adjusting to the pressure during navigation itself by bouncing back to the appropriate trajectory, thus increasing accuracy. Additionally, the Excelsius GPS integrated surveillance system constantly monitors the navigation system and notifies neurosurgeons when the system is jeopardized [14].

5. Limitation of spinal-robotics in spinal surgery: Learning curves

Spinal-robotics can be seen to be extensively analyzed as they have advanced through the field in the past few decades. Many platforms are introduced focusing on resolving the shortcomings of conventional techniques used in pedicle screw placements in the past, such as decreasing radiation exposure, reducing blood loss, reducing post-surgical complications, scoring highly in the Gertzbein and Robbins grading system, shortening surgery duration, overcoming limitations of human ability, and most importantly, more automation with fewer errors. Much research has been made to elaborate on many aspects of robot-assisted spinal surgery, but whether these techniques rely on users' experience has been glanced over [7].

One limitation that arose, which is inevitable with the extensive refinement incorporated but is currently rarely discussed, is the learning curve [7]. The learning curve was first introduced by T.P. Wright, who entered aircraft manufacturing in 1936. It was then brought into light in the medical field in the 1980s following the invention of minimally invasive surgery. The concept originated from the Bristol Royal infirmary, mainly indicating that as surgeons gained more experience, the performance of the interventional techniques improved. A study done by applying regression analysis has shown the performance of surgery has plateaued for the first 20 cases [7]. The learning curve is defined by the time or frequency required for surgeons to master the techniques, as measured by blood loss, surgery duration, morbidity rates and other factors [19].

It is crucial to investigate as a surgeon's capability of learning to incorporate robot assistance into the surgery procedure could affect the duration of the operation, the accuracy of pedicle screw placement, and, most importantly, the complications that come after it [17]. Moreover, research has shown that one of the pitfalls of the application of robots in spinal surgery is the arduous learning curve and lengthy setup durations [6].

6. Conclusion

As technology has advanced in the surgical field, alternative methods such as freehand technique, assisted fluoroscopy, or computer tomography have been developed, focusing on the flaws. However, the complications accompanied by these methods did not create an ideal intraoperative environment. This led to the development of robotic surgery, which has proven its ability to counter the downsides of alternative methods. Despite its invention, the implementation of robotic surgery in the spinal surgical field has been notably sluggish due to its stringent demand for accuracy. Furthermore, more and more attention has been drawn towards the limitation such as learning curves of robotics in spinal surgery.

Based on the current research, many flaws still lie within the range of accuracies, and robotic navigation has yet to be involved in artificial intelligence. Integration of artificial intelligence into spinal surgery is highly beneficial could for the maturation by continuous learning and improving with surgical data and experiences. Additionally, the automation process can mitigate the downsides of human limitation such as shorten the surgery and reducing errors inducing by fatigues during long duration surgery. Furthermore, cases of spinal surgery that employ robotics can be expected to expand widely. New inventions can be incorporated, such as automatic planning of pedicle screws using machine learning.

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