Chapter

Robotic-Assisted Systems for Spinal Surgery

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Abstract

Robotic-assisted spinal surgery is in its infancy. It aims to improve the accuracy of screw placement, lower the risk of surgical complications, and reduce radiation exposure to the patient and the surgical team. The present chapter attempts to provide an overview of the evolution of robotic-assisted spinal surgery and highlights different commercially available spine robotic systems in present use. The review concludes with future applications of robotics in spinal surgery.

Keywords: robotics, spine surgery, pedicle screws, radiation, shared-control system, CT scans, fluoroscopy

1. Introduction

Stereotaxy was coined by Victor Horsley and Robert Clarke in 1908 to describe a method of locating points within the brain by using the Cartesian coordinate system that measures distance from a fixed reference point derived from external cranial landmarks [1]. This was followed by the development of image guidance in 1986, which integrated stereotaxy with computed tomography [2]. The development happened in the backdrop of transition from frame-based to frameless stereotaxy based on enhancements in spatial fidelity of imaging data, computational power, and 3-D digitizers [3]. However, spinal surgery applications of the image guidance systems arising from these refinements carry limitations. These include dependence on a direct line of sight between the optical tracking system and navigated instruments for ensuring screw insertion accuracy and a learning curve for using the navigation system. The learning curve comes from the fact that the surgeon now has to redirect his or her eyes from the patient to the navigation screen in order to follow the planned trajectory for screw placement. This can result in surgical errors since attention is taken away from the patient at the point of screw insertion. An attempt to address this shortcoming has led to the development of robotic systems that utilize similar image guidance platforms while physically guiding the surgeon to the preplanned trajectory for screw placement [4, 5].

The field of spinal surgery is characterized by a unique set of defining features such as the need for high order of surgical precision as several critical structures are located in close proximity of the vertebral column. Injury to these structures, which include blood vessels and nerves, can lead to a wide spectrum of consequences ranging from pain to paralysis. The close association of critical structures is compounded by the narrow operating corridors for doing surgeries involving the spinal column. This set of challenging circumstances strengthens the case for robots as surgical assistants due to the lack of fatigability while undertaking tasks repeatedly and without showing a reduction in performance. Since the introduction of da Vinci Surgical System (Intuitive Surgical, Sunnyvale, CA), cleared for use by the Food and Drug Administration (FDA) in 2000, the field of robotic surgery has continued to mature and gain more widespread acceptance. However, the field of neurosurgery has seen growing interest only in recent times for the use of surgical robotic systems to assist the surgeon in operative procedures.

With surgical robots becoming more visible in a number of surgical disciplines, the various systems in use can be broadly classified into three main categories depending on the interaction of the surgeon with the robot [3]. The first category is supervisory-controlled systems where the actions carried out by the robot are preprogrammed by the surgeon who then monitors the robot performing the specified steps autonomously. The second type is the telesurgical systems where the surgical manipulator follows the movements of an input device directly manipulated by the surgeon in a master-slave manner. The third type is the shared-control models where the motions are concurrently controlled by both the surgeon and the robot via shared control of the surgical instruments. Despite the shared control, the surgeon remains in charge of the decision-making related to the procedure with the robot providing steady-hand manipulation of the instruments [3]. All the surgical robots approved by the FDA for spinal procedures fall under the third category of shared-control systems.

To this point, robotics have largely been utilized in placement of pedicle screws and shown comparable and/or superior accuracy of screw placement compared to conventional, freehand technique of screw placement [6–8]. Despite the initial encouraging findings, the adoption of surgical robots has been relatively slow among the spine surgical community with robots not yet considered as part of the routine standard operative procedure for spinal indications. A major concern for the tepid response to robots is the significant capital investments required for the surgical robot and the associated navigation equipment. The use of navigation systems irrespective of surgical robots is still not commonplace across the surgical suites, which places training requirements on top of the added cost. Further compounding the situation is the perception that adding steps to the operation workflow would lead to increased operation time and decreased efficiency. Given the limited scientific literature on operative and clinical outcomes, there is skepticism toward robots by the surgical community. In the present article, we attempt to explore the evolution of robotic-assisted spinal surgery to where the field stands now and conclude with future applications.

2. Commercial surgical robotic systems in current use

The last two decades have seen the introduction of several robotic systems in spinal surgery but the Food and Drug Administration approval has been granted to three of these systems (**Figure 1**). These include SpineAssist® (Medtronic Inc., Dublin, Ireland), ROSA® (Medtech S.A., Montpellier, France), and ExcelsiusGPS® (Globus Medical Inc., Audubon, PA). SpineAssist®, which received both FDA clearance and European CE Mark of approval in 2004, was the first robotic assistance system to be used in the spinal surgery. Subsequent iterations of SpineAssist®, Renaissance®, and Mazor X™ were released to address some of the limitations of SpineAssist® and received both FDA and CE approval in 2011 and 2017, respectively. The most recent follow-up of SpineAssist® is Mazor X™ Stealth Edition, which received FDA clearance in 2018. The second system approved for commercial use, ROSA®, obtained CE Mark of approval in 2014 FDA clearance in 2016, while the most recent surgical robot system, ExcelsiusGPS®, received both FDA and CE approvals in 2017.

Figure 1.
Systems for robotic-assisted spine surgery: Mazor Renaissance® (A), Mazor X™ (B), ROSA® (C), and ExcelsiusGPS® (D).

2.1 SpineAssist®

SpineAssist® was the first commercially available system for robotic-assisted spinal surgery. It comprises a cylindrical device mounted to a patient-specific anatomical landmark, which relies on pre- and/or intraoperative CT imaging to allow trajectory planning for screw insertion. Subsequent iterations of SpineAssist® include Renaissance® followed by Mazor X™ (list price ~US$1.2 M) with the latter consisting of an independent robotic arm where the attachment to the patient is done using a single pin in place of a robot-mounted platform as is the case with the former. Medtronic Stealth System is used concurrently to provide navigation. Recently, Mazor X™ Stealth Edition has been released, which also obviates the need for K-wires and a separate navigation system. Like the previous versions, it requires the robotic arm to be mounted to the bedframe.

2.2 ROSA®

The second system approved by the FDA is the ROSA®, which works similar to the SpineAssist® in using pre- or intraoperative CT imaging to plan screw trajectory but provides the additional convenience of built-in navigation for determination of screw depth.

2.3 ExcelsiusGPS®

ExcelsiusGPS®, the third and most recently approved commercial robotic system (list price ~US$1.2 M), has a built-in navigation system similar to ROSA® but does not require attachment to the patient or the operating table. In addition, it removes the need for a K-wire by providing an end effector for the passage of instruments and detecting "skiving" of instruments. There is also a secondary passive reflective marker to monitor the accuracy of robotic navigation system.

Robotic system	Navigation	Direct implant placement	K-wire required	Imaging			Portability
				Intra-op	Pre-op	Fluoroscopy	
Renaissance	Separate	No	Yes		✓		Patient mounted
Mazor X	Separate	No	Yes	✓	✓		Bed mounted
Mazor X Stealth Edition	Integrated	Yes	No	✓	✓		Bed mounted
ROSA	Integrated	No	Yes	✓			Free standing
ExcelsiusGPS	Integrated	Yes	No	✓	✓	✓	Free standing

Table 1.
Comparison of commercially available spine robotic systems.

Table 1 highlights salient features of each of the surgical robotic systems.

In the subsequent section, the experience with the use of these systems is described followed by an appraisal of the limitations of the present systems and avenues for future research. Due to relative longevity of SpineAssist® availability for commercial application, a significant portion of the published literature is based on the experience of using SpineAssist® and its subsequent iterations, Renaissance® and Mazor X™.

3. Applications of robotics in spinal surgery

3.1 Pedicle screw instrumentation

Despite being the most commonly performed procedure related to the thoracolumbar spine, a steep learning curve is associated with transpedicular fixation. Subsequently, the primary application of surgical robots in spinal surgery has been transpedicular fixation. The use of robotic surgical assistants in transpedicular fixation arose from the wide variability of findings about accuracy of screw placements reported for various versions of conventional, fluoroscopic-dependent techniques. The results on the accuracy of pedicle screw instrumentation using surgical robotic assistants have been largely superior to the manual screw insertion using fluoroscopy. The commonly accepted method of determining insertion accuracy involves the use of postoperative CT scans, which despite providing radiographic confirmation of screw placement is limited in divulging the clinical implications of the radiographic findings. This limits the inferences that can be drawn to some extent, but given the popularity of this method of comparison, the various robotic systems are discussed with respect to screw insertion accuracy.

A detailed evaluation of the scientific literature highlights that a significant share of studies document results from SpineAssist® and its iterations, namely, Renaissance® and Mazor X™. The first account on the use of robotics was provided by Sukovich et al. in a 2006 retrospective analysis, which used SpineAssist® in 14 patients for the placement of 98 pedicle screws through a combination of open and minimally invasive techniques. The authors showed that 96% of the screws were within 1–2 mm of the planned trajectory with no cases of pedicle breach [9]. In another study, Pechlivanis et al. looked at the screw insertion accuracy of SpineAssist® during minimally invasive posterior lumbar interbody fusion (PLIF). The accuracy was determined on postoperative CT scans using the Gertzbein and Robbins system (GRS) for evaluating the accuracy of pedicle screw insertion [10, 11]. The GRS grades the screws into four categories based on the location of the screw within the pedicle: Grade A, screw is completely within the pedicle; Grade B, screw breach is <2 mm; Grade C, screw breach is >2 and <4 mm; Grade D, screw breach is >4 and <6 mm; and Grade E, screw breach is >6 mm. Grades A and B are considered acceptable for screw accuracy. Of the 122 screws inserted, with the exception of one screw that was Grade D, the remaining screws were either GRS Grade A (108) or GRS Grade B [13]. Devito et al. performed a multicenter, retrospective review comprising of 3271 pedicle screws placed with SpineAssist® and showed 98% of the screw insertions to be acceptable when assessed by intraoperative fluoroscopy. Further, accuracy measurements done on postoperative CT scans in a subset of these screws (646) showed over 98% of the screws fell within the safe zone (GRS Grades A and B) [12]. In a study involving 112 patients and 494 screws using SpineAssist®, van Dijk and colleagues found a 97.9% rate of clinically acceptable screw insertion [13]. Hu et al. evaluated 960 pedicle screws placed with Renaissance® and found that 949 screws (98.9%) were placed accurately [14]. A separate study by the same group showed successful screw placement in nine patients with spinal column tumors [15]. In a review of 50 patients with adolescent idiopathic scoliosis (AIS) that underwent robotic MIS posterior spinal fusion, Macke et al. evaluated a total of 662 pedicle screws inserted using Renaissance®. The authors observed a 92.7% acceptable placement rate. Lower rates of screw malpositioning were noted with robotic MIS than prior published data, and improved accuracy of screw insertion was observed when using preoperative CT obtained in the prone position [16].

A number of studies have compared accuracy between conventional freehand and robotic-assisted procedures. In a retrospective analysis, Kantelhardt et al. used SpineAssist® and performed pedicle screw placement accuracy comparisons between three groups, namely, conventional freehand versus open robotic-assisted versus percutaneous robotic-assisted, and showed comparable accuracy rates for the combined robotic-assisted groups (94.5%) and the freehand group (91.4%) for screw insertion [17]. Schatlo and colleagues used SpineAssist® and demonstrated similar rates of clinically acceptable screw placement between open fluoroscopy-guided and robotic-assisted placement (open and percutaneous) groups [18]. In a separate analysis by the same group, the impact of experience of surgeon on screw insertion accuracy was evaluated for 1265 pedicle screws. The authors showed 1217 (96.2%) screw placements were of an acceptable grade with screw misplacement peaking between the first 10 and 20 surgeries and declining as more surgeries were performed by the surgeon [19]. The same group followed this up with an analysis involving 169 patients that underwent posterior instrumentation for spinal instability and showed a higher proportion of non-misplaced screws in the robot (93.4%) than the freehand fluoroscopy-guided cohort (88.9%), which was statistically significant [20]. Schizas et al. evaluated robot-assisted (open or percutaneous) versus fluoroscopy cohort and showed comparable accuracy rates with 95.3% for the robotics group and 92.2% for the freehand group [21]. The accuracy of screw insertion was assessed using the Rampersaud scale, which describes the relative position of the screw to the pedicle and comprises the following four grades: Grade A, completely in; Grade B, <2 mm breach; Grade C, 2–4 mm breach; and Grade D, >4 mm breach [22]. Solomiichuk and colleagues performed a retrospective matched cohort study in 70 patients diagnosed with metastatic spine disease and showed grade A or B screw placement in 162 of 192 (84.4%) in the robotic-assisted group and in 179 of 214 (83.6%) in the conventional group with no differences in screw accuracy between the groups. Further, no differences were found between the cohorts for accuracy, duration of surgery, radiation exposure, or surgical site infection with the exception of intensity of radiation [23]. Keric et al. evaluated 90 patients treated for spondylodiscitis with posterior spinal fusion via either conventional, open free-hand, or percutaneous robot-assisted spinal instrumentation using Renaissance®. Their findings revealed robotic cohort was associated with higher accuracy and lower likelihood for revision procedures for improper screw placement. Further, the robotic-assisted MIS cohort had lower intraoperative fluoroscopy and shorter postoperative stay [24]. In a separate review of 1857 implanted screws, Keric and colleagues showed increased rates of screw deviation in clinical diagnosis such as tumor, infection, and osteoporotic fractures [25]. In another review of 206 patients with spondylodiscitis that underwent posterior spinal fusion, Alaid et al. observed a lower rate of revision for wound breakdown in the robotic MIS group using SpineAssist® than the open, freehand group [26].

The comparison of screw accuracy between freehand and robotic-guided screw insertion has also been analyzed through a number of randomized controlled trials. Kim et al. compared the accuracy and safety of screw insertion between robotic-assisted minimally invasive PLIF using Renaissance® (37 patients) and conventional, freehand technique for PLIF (41 patients). For intrapedicular accuracy, no significant differences were observed between the groups. Of the 74 screws in the robotic cohort, none breached the proximal facet joint, while 13 of the 82 screws in the freehand group violated the proximal facet joint ($P < 0.001$). Further, the average distance of the screws from the left and right facets was significantly smaller in the freehand group [27]. Roser et al. used SpineAssist® to compare screw accuracy between fluoroscopic-guided freehand, navigation-guided, and robotic-assisted screw instrumentation. The authors found no significant differences for screw accuracy between the different techniques, but the conclusion was not backed by statistical analysis due to small study size [28]. Ringel et al. compared an equal number of patients randomly assigned to either percutaneous screw placement using SpineAssist® or conventional, open freehand technique. The results of their RCT differ from the large majority of studies in that a lower rate (85%) of clinically acceptable screw placement was reported for robotic-guided technique than the freehand technique (93%) for screw insertion [29]. Hyun and colleagues performed a prospective study comparing fluoroscopy-guided approach with MIS screw insertion using Renaissance® in lumbar fusions. The authors observed all screws in the robotic group were placed accurately, while in the freehand group, the accuracy rate was 98.6% [30]. In a prospective analysis, Park and colleagues compared 37 patients with MIS screw insertion using Renaissance® and 41 patients that underwent freehand technique for pedicle screw insertion during posterior interbody fusion surgery. They showed both groups had similar improvement in clinical outcomes at 2-year follow-up [31].

Aside from studies on SpineAssist® and its iterations, only a small number of publications have explored other surgical systems. Lonjon et al. compared screw placement using the ROSA® with freehand technique of screw insertion. The authors found a 97.2% accuracy rate in the robotic group and a 92% accuracy rate in the freehand group [32]. In a study by Huntsman et al., MIS screw placement using ExcelsiusGPS® showed 99% of screw placed successfully based on the surgeon's interpretation of intraoperative plain film radiographs, with no cases of screw malposition requiring revision surgery [33].

3.2 Other applications

Bederman et al. evaluated the utility of SpineAssist® or Renaissance® robotic system in the placement of S2-alar-iliac screws and found all screws are placed accurately with no breach of the anterior sacrum [34]. Hu et al. performed a retrospective analysis of 18 patients who underwent S2AI fixation with assistance from Renaissance® robotic system and found accurate screw trajectory on postoperative CT scans without any violations of iliac cortex or breaches of the anterior sacrum [35]. In another study comprising of four adult spinal deformity patients who underwent minimally invasive robotic-guided insertion of S2-alar-iliac (S2AI) screws using Renaissance® robotic system, Hyun et al. observed all the screw trajectories were positioned accurately based on postoperative X-rays and CT scans [36]. Laratta and colleagues evaluated S2AI screw insertion in 23 consecutive patients who underwent spinopelvic fixation with Renaissance® robotic system and noted two violations of iliac cortex but no neurologic, vascular, or visceral complications among the 46 S2AI screws that were inserted [37]. In a retrospective matched cohort analysis, Shillingford et al. compared robotic-assisted using Renaissance® robotic system (23 patients, 46 screws) and conventional, freehand (28 patients, 59 screws) S2AI screw placement in 68 consecutive patients with spinal deformity. The authors observed no differences between the groups for screw insertion accuracy or intraoperative complications [38].

4. Illustrative case examples

4.1 Case 1: MIS robotic-assisted thoracolumbar instrumentation for adult trauma

A 44-year-old healthy man presented to the hospital following a 12-ft fall from the roof of a house while repairing it. He complained of severe back pain with right-sided leg numbness. Physical examination demonstrated severe pain and numbness in the lower limbs. On CT, a burst fracture at L1 was observed with MRI showing injury to the posterior ligamentous complex (PLC) (**Figure 2**). The decision-making for the clinical management for the patient was evaluated using the thoracolumbar injury classification and severity score (TLICS), a classification system for thoracolumbar injuries that predicts the need for surgery [39]. It comprises three independent predictors, which are morphology, integrity of PLC, and neurological status. The patient presentation was given a TLICS score of 7, and consequently the patient underwent robotic-assisted MIS T11-L3 fixation and fusion (**Figure 3**). The patient had complete recovery.

4.2 Case 2: open robotic-assisted thoracolumbar fusion for pediatric trauma

A 13-year-old boy presented to the hospital after landing on his upper back while attempting to jump out of a swinging hammock. He reported thoracolumbar pain, which was located in the hip region but had no radicular pain into the lower abdomen

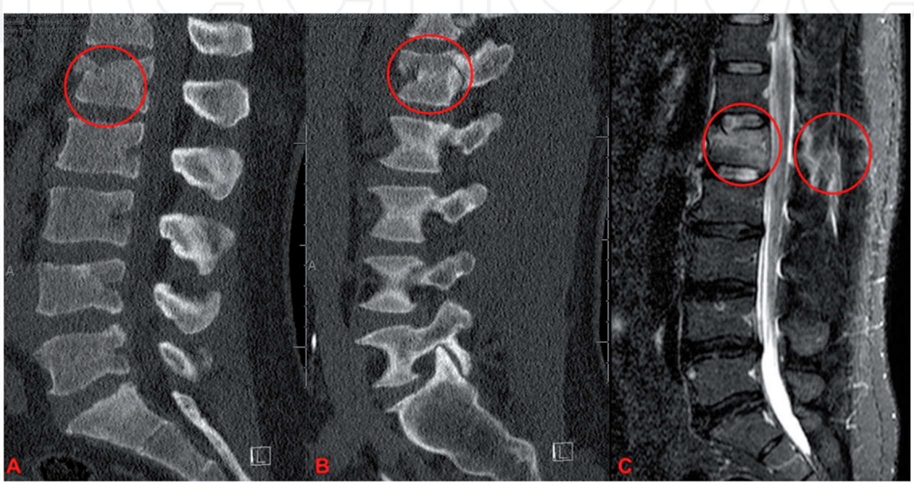

Figure 2.
Case 1: Preoperative CT (A and B) and MRI (C) showing L1 burst fracture with injury to the posterior ligamentous complex (red circles).

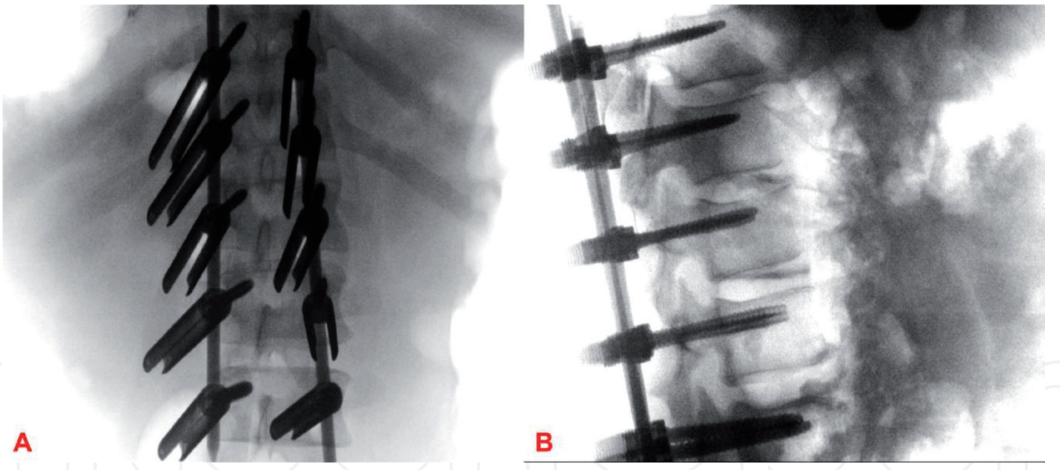

Figure 3.
Case 1: Intraoperative X-rays showing MIS T11–L3 transpedicular fixation (A and B).

Figure 4.
Case 2: Preoperative MRI showing T11–T12 anterolisthesis, T12 wedge fracture with T11–T12 facet dislocation, and posterior ligamentous injury with small dorsal epidural hematoma (red circle).

or legs. MRI revealed T11/T12 anterolisthesis, T12 wedge fracture with T11–T12 facet dislocation, and posterior ligamentous injury with small dorsal epidural hematoma (**Figure 4**). CT thoracic spine showed fracture and subluxation at T11–T12 with bilateral perched T11 facets, right pedicle fracture of T12 extending into the superior end plate of the vertebral body with wedging of T12 along with anterior and inferior displacement of the anterior ring apophysis, and spinous process fractures of T11 and to a lesser extent T10 (**Figure 5**). Based on the clinical presentation and imaging findings, a decision to operate was made. The patient underwent robotic-assisted T10-L1 fixation and fusion, T11/T12 open reduction and internal fixation at T11–T12, and T11 laminotomy for epidural hematoma evacuation (**Figure 6**). The patient had complete recovery and subsequently underwent removal of the hardware at 1 year.

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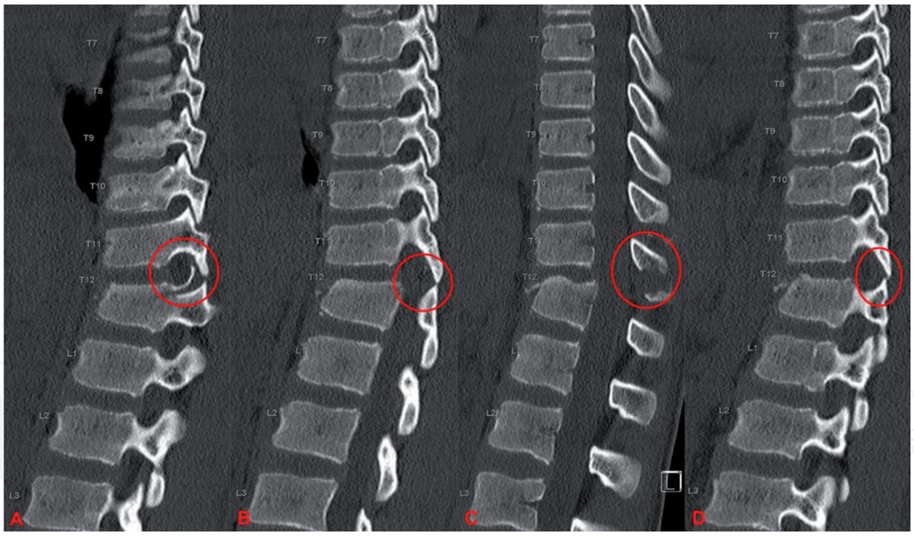

Figure 5.
Case 2: Preoperative CT thoracic spine (A–D) showing bilateral T11–T12 facet dislocation, bilateral perched facets, and T10 spinous process fracture (red circles).

4.3 Case 3: MIS robotic-assisted TLIF for degenerative spine

A 58-year-old female presented to the hospital with back and leg pain. The leg pain was on the left side and radiating to the left foot. The patient mentioned the back pain was worse than the left lower extremity (LLE) pain with duration of pain progressing over the last 2 years. Additionally, she complained of LLE weakness and numbness as well as cramping in bilateral calf muscles. Imaging showed 11 mm L4/5 anterolisthesis on standing XR (**Figure 7**) and severe spinal stenosis at L4/5 on MRI (**Figure 8**). Her medication history included hydrocodone, meloxicam, and tizanidine. Due to the long duration of the pain, the patient had tried a number of conservative treatments such as chiropractic, transcutaneous electrical nerve stimulation (TENS), and heat/ice packs but mentioned that none of these treatments had

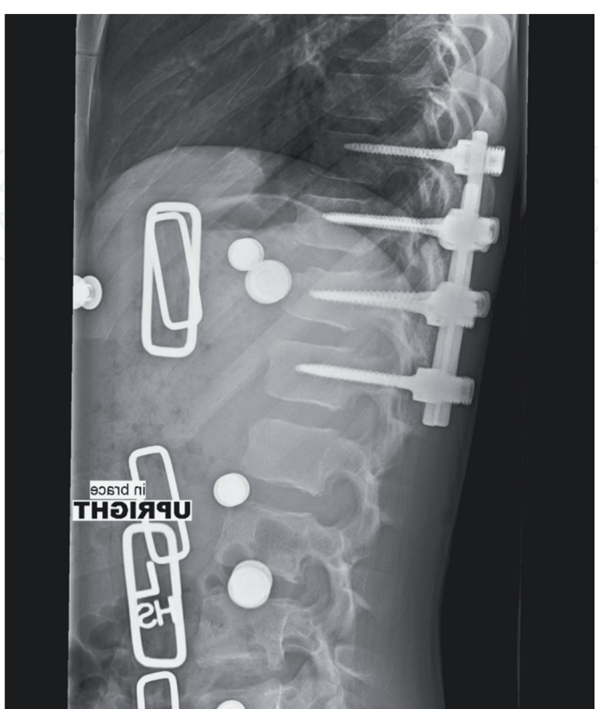

Figure 6.
Case 2: Postoperative X-ray showing T10–L1 transpedicular fixation and restoration of spinal alignment.

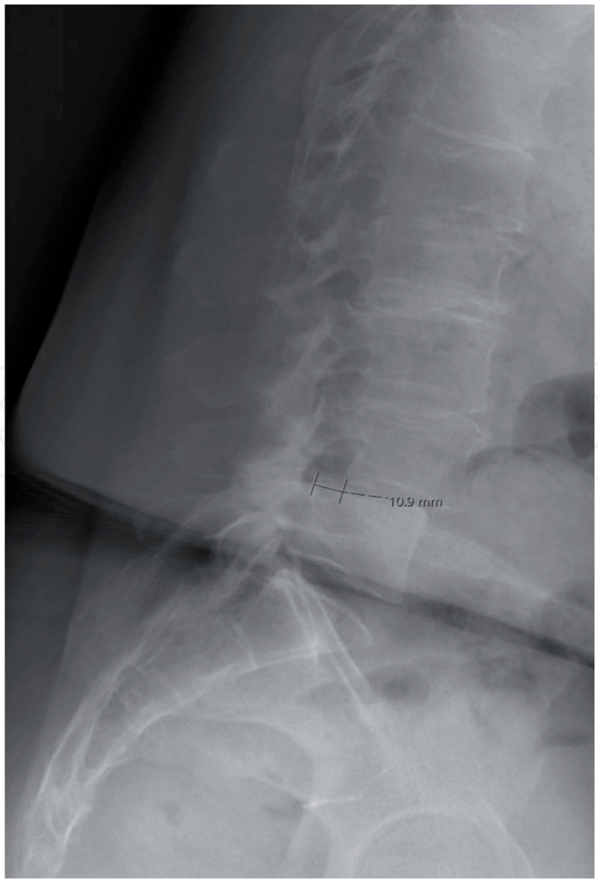

Figure 7.
Case 3: Preoperative standing X-ray showing 11 mm L4/5 anterolisthesis.

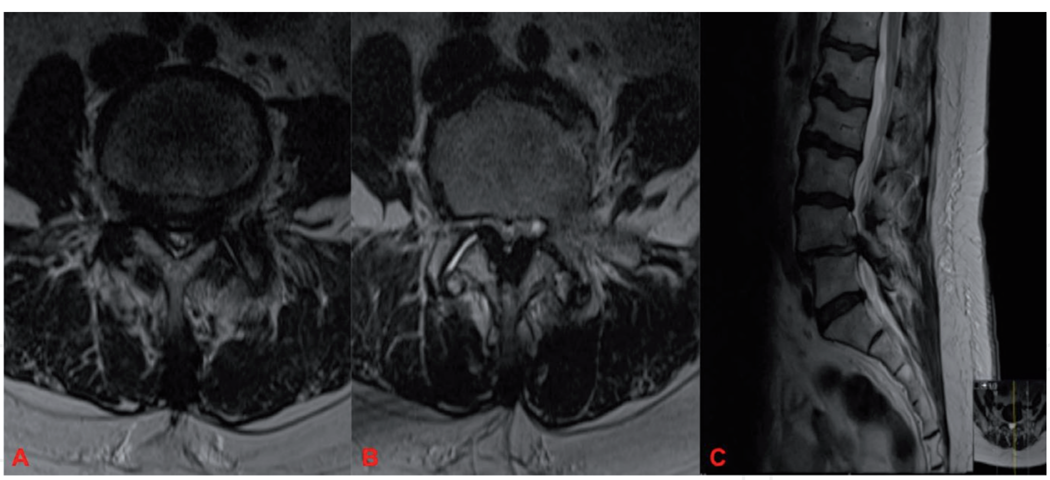

Figure 8.
Case 3: Preoperative MRI in axial (A and B) and sagittal (C) planes showing severe spinal canal, lateral recess, and foraminal stenoses at L4–5.

worked for her. Based on the clinical presentation and imaging findings, a decision to surgical operation was made, and the patient underwent an MIS robotic-assisted transforaminal lumbar interbody fusion (TLIF, **Figure 9**). The patient was discharged within a day and had resolution of back and leg symptoms on follow-up.

4.4 Case 4: hybrid MIS robotic-assisted cervicothoracic fusion for adult trauma

A 30-year-old female presented to the hospital after being involved in a rollover motor vehicle accident. Physical examination demonstrated severe neck pain and tingling in the left arm. On imaging, she had left C5–C6 facet fracture dislocation

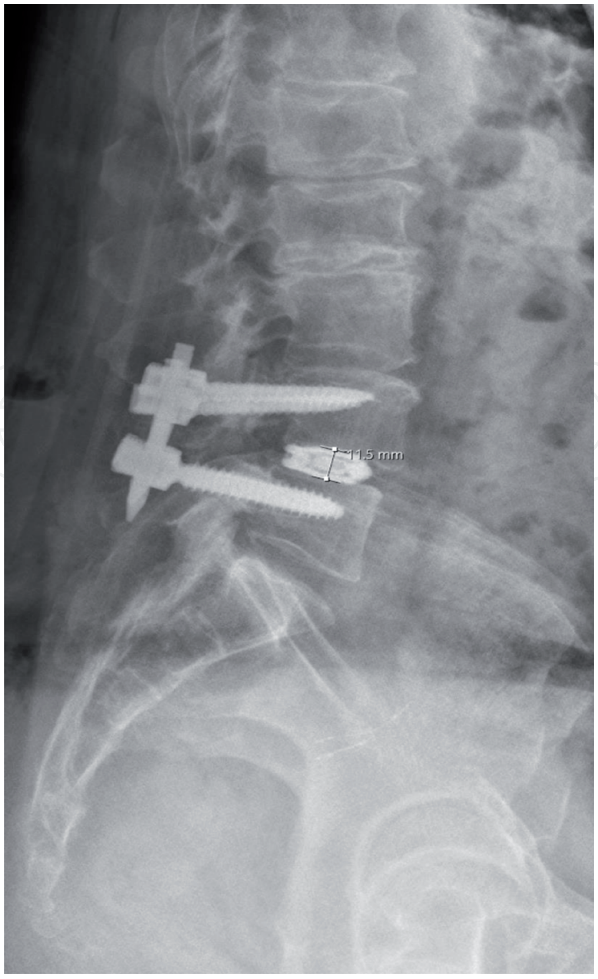

Figure 9.
Case 3: Postoperative standing X-ray showing L4–5 transforaminal lumbar interbody fusion with spondylolisthesis reduction and disc height restoration.

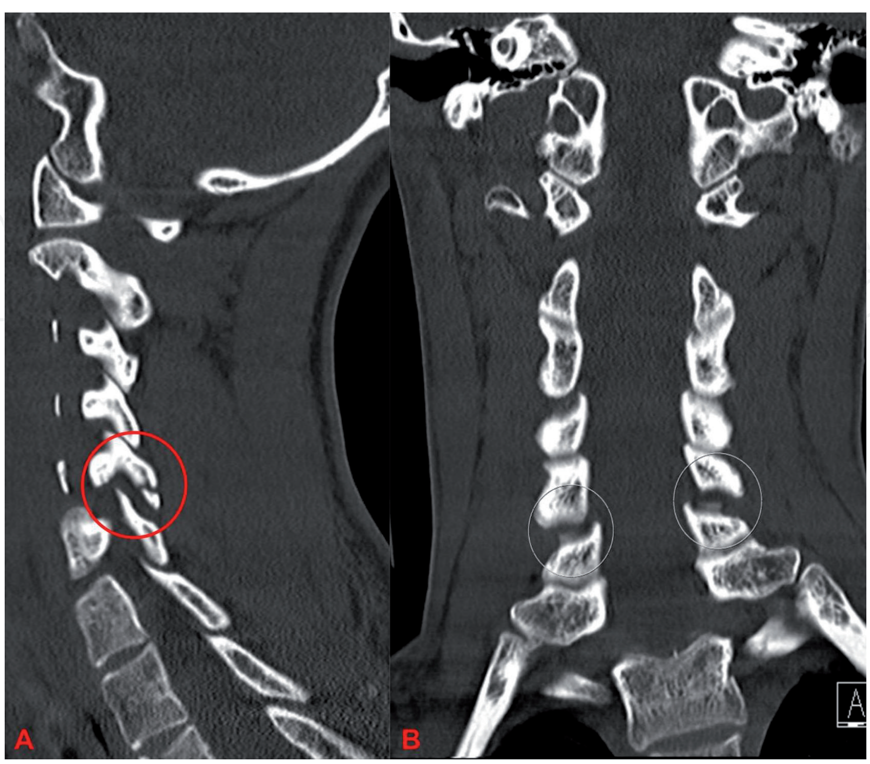

Figure 10.
Case 4: Preoperative CT showing C5–C6 facet fracture dislocation and bilateral C5–C6 facet distraction (red and gray circles).

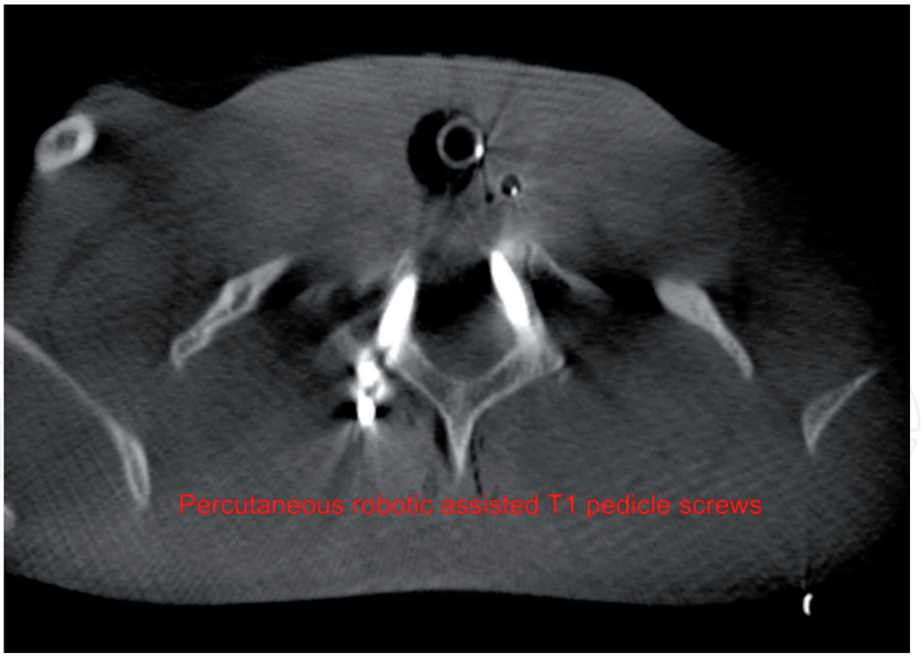

Figure 11.
Case 4: Intraoperative CT showing percutaneous robotic-assisted T1 pedicle screws.

and bilateral C5–C6 facet distraction (**Figure 10**). The patient underwent C4-T1 fixation and fusion with percutaneous MIS robotic-assisted T1 pedicle screws (**Figure 11**). Her midline incision could be minimized to approximately 3 inches. She had complete recovery and was discharged to the rehabilitation unit.

5. Discussion and future directions

Radiation exposure is an important consideration when comparing the utility of robotics in spinal surgery to conventional, fluoroscopic techniques. With expanding indications for the use of MIS in more complex spinal cases, the concern about radiation is a major factor in technology adoption going forward. Recognizing the impact of this issue on increased adoption of robotics, a number of studies have looked at the radiation exposure in patients operated with the assistance from surgical robotics vis-à-vis patients treated with conventional, fluoroscopic techniques. Based on the limited literature on this topic, it appears the incorporation of robots in the operating workflow is associated with reduction in both the time and the levels of radiation exposure [40]. In a prospective randomized controlled trial, Hyun et al. observed shorter radiation times and output in the robotic group, which was statistically significant [30]. Kim and colleagues noted a significant reduction in fluoroscopy duration in later cases when compared to the early cases [41]. In a study comparing different guiding methods for pedicle screw insertion, Fan et al. showed that robotic-assisted technique was associated with shorter fluoroscopic time than conventional, freehand technique or O-arm-based navigation but longer time than patient-specific navigational template technique [42]. Another study looking at different screw insertion guiding techniques showed the lowest dose of radiation in the standard navigation group, which was followed by the robotic group and then the conventional, freehand group [28]. Kantelhardt et al. found that robotic-assisted screw insertion had statistically significant lower radiation exposure than conventional, freehand technique. However, the authors found no difference between percutaneous and open robotic-assisted pedicle screw insertion [17]. Similarly, Keric and colleagues noted lower fluoroscopy time in the robotic-assisted screw insertion cohort [24]. In contrast, Ringel et al. and Schizas et al. found no differences in radiation exposure between the robotic and the freehand groups [21, 29]. Based on published data, it appears that robotic-assisted procedures lead to reduction in radiation exposure with the greatest value addition of robots being in percutaneous screw insertion. The use of robots in this case has the potential to reduce the radiation exposure, which tends to increase dramatically for conventional screw insertion techniques. The end result of incorporating robotics could obviate the need for lead apron by the operating room staff.

When compared with navigation, the use of robotics allows for preplanning of screws. This saves operative time and allows the operating room staff to prepare implants ahead of time. By preparing for any anatomical variations that the surgeon might encounter (such as in deformity, trauma, and previously arthrodesed spines), the robot can be deployed for spinal procedures that involve more complex anatomical relationships. Over time, enhancements to graphical user interface have simplified the screw trajectory planning. By allowing the superimposition of intraoperative scans over preoperative imaging, the robots help the surgeon to take into consideration patient movement to more accurately plan the procedure while also providing the surgeon with the ability to select optimal screw dimensions. By taking into account patient immobilization, a robotic surgical assistant can lead to a diminished operating time while reducing pedicle and vertebral body violations. Further, the visualization provided by the robotic software platform can aid in rod contouring/placement through optimized screw cadence and skin incision optimization for MIS procedures in obese patients.

The experience with the use of surgical robots in spine surgery has been positive so far with a large majority of studies documenting outcomes observed with robots that are equal or superior to the findings observed with conventional, openhand technique. This is on account of the reduction of human manual error as the robot provides a stable, rigid channel for guiding surgical instruments by the surgeon. The same advantage holds true when compared to navigation-assisted screw placement, which is more prone to deviations due to lack of a stable conduit for maneuvering instruments. Further, the ability to lock trajectories allows for repeatability during surgical procedures by limiting the influence of physiological hand tremor, which allows for efficiency gains over time. This element of repeatability has the added benefit of providing the surgeon the ability to better plan skin incisions. Despite the possible advantages of robots, the capabilities of the present robotic systems are fairly limited, which only favors their role in a narrow, specific set of indications as evident from most of the present literature being on the use of robots for primarily pedicle screw fixation. However, it is crucial to acknowledge the results by Ringel et al. that noted lower screw insertion accuracy with the use of surgical robotic system. A number of possible reasons could have led to these findings including lateral skidding of the cannula at the entrance point caused by the steep slope of the lateral aspect of the facet joint or using a platform fixed to a cranial spinal process with a K-wire and attached to the operating table by a bed mount, which meant the robot was only attached to the patient via a single K-wire [43].

With robotics continuing to become more visible in the spinal surgery, a discussion of future areas of developments is warranted. A major thrust for moving the field of robotics forward would involve arriving at reproducible definitions of screw trajectory that mitigate the interruptions to the surgical workflow caused by the present manual method of trajectory planning. Knez and colleagues employed nonparametric models of vertebral bodies and pedicles registered to the patient CT while also accounting for spinal curvature to calculate automatic trajectories that showed close agreement with manually defined plans [44, 45]. In a study based on an atlas-based method that incorporated patterns of biomechanically optimal constructs and a surgeon's own planning preferences, Vijayan et al. highlighted a method that is generalizable to other surgical planning applications [46]. The abovementioned methods are not only built on the premise of introducing consistency to screw trajectories but also hold potential for the estimation of screw diameter(s) and length(s) to be used in a given operation.

Perhaps the greatest challenge impeding the growth of robotic systems stems from the inability of present systems to utilize visual cues from the surroundings to identify objects both accurately and automatically. Therefore, the functionality of a robot is completely modeled by the humans, and accordingly robots are only able to perform tasks for which they are preconfigured. The present state of affairs shows the path forward, which in all likelihood will see robotics integrating with artificial intelligence (AI) to confer robots with increased accuracy in visual identification and autonomous decision-making capacity. This would entail competing with visual systems seen in humans where two-dimensional inputs from the environment are collected by the human eye and converted into three-dimensional interpreted by the brain. Further, the surgical environment is a dynamic one and responding in such a way an environment would need sequential processing of external stimuli in real time. This is necessary for the robots to transition from mere translators of preprogrammed structured scenarios to dynamic adaptors in the external world. The enhancements to spatial and temporal visual information processing capabilities bring to attention the central role of neural networks in bringing these capabilities online. Modeled on the parallel processing structure of the human brain, an artificial neural network is composed of interconnected processing elements. Neural network learning is driven by the training algorithm autonomously and continually adjusting the connection weights based on exposure to input/output data. By being exposed to the surgeon's screw planning preferences, the robot would over time be able to automatically plan the screws for the surgeon. Further, machine learning could be utilized to pool data from several surgeons and make use of their combined expertise to suggest optimized screw trajectories over the cloud, irrespective of the geographical location of the surgeon.

As technological adoption increases among the younger generations of surgeons, virtual reality (VR) platforms for skills acquisition and operative planning among other function would grow in demand. While a virtual depiction of the operating environment is imperative from an educational point of view, the superimposition of virtual objects over real-world environment via hybrid systems known as augmented reality (AR) is needed for enhanced manipulation. An example of such a scenario would perhaps include head-mounted visor that projects screw trajectory in front of the surgeon on a virtual display with the surgeon not located in the immediate vicinity of the patient. This would demand capabilities for seamless, real-time transmission and integration of stereoscopic images defining the operative field and imaging data defining the patient anatomy. The rise of AR could also be instrumental in ushering remote collaboration between surgeons located at distant geographic locations. This would need improvements in information transmission capabilities to allow for real-time collaboration, an area where fifth generation (5G) network technology might be of assistance. However, these developments speak to a more distant future, and in the more immediate time frame, robotics in spinal surgery might come to resemble the da Vinci Surgical System, a slave master system, where the surgeon sits at a console and controls the robot.

Of note, the enhanced capabilities would need to be designed in a manner that makes the robot a hand dexterity enhancer for the surgeon while still being in full control by the surgeon. As robotic technology becomes more sophisticated, the move toward autonomous robots will raise concerns about the transfer of control from the surgeon to the robot and the growing dependence of the surgeon on the in-built systems of the robot. Further, the possibility for real-time collaboration among physicians for screw planning recommendation as well doing the actual screw placement will raise concerns about patient consent, medical liability, and data confidentiality, among others. These are relevant ethical challenges of our time that demand more research into crucial areas of robotic design related to both software and hardware as well as the medicolegal requirements protecting the patient such as the Health Insurance Portability and Accountability Act (HIPAA).

6. Conclusions

The current state of robotics in spinal surgery is comprised of a limited range of clinical indications related to screw placement. With emerging data showing acceptable rates for screw insertion and radiation exposure, the field of robotics is expected to benefit from further technological developments.

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