# Spinal Robotics: Current Applications and Future Perspectives

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Even though robotic technology holds great potential for performing spinal surgery and advancing neurosurgical techniques, it is of utmost importance to establish its practicality and to demonstrate better clinical outcomes compared with traditional techniques, especially in the current cost-effective era. Several systems have proved to be safe and reliable in the execution of tasks on a routine basis, are commercially available, and are used for specific indications in spine surgery. However, workflow, usability, interdisciplinary setups, efficacy, and cost-effectiveness have to be proven prospectively. This article includes a short description of robotic structures and workflow, followed by preliminary results of a randomized prospective study comparing conventional free-hand techniques with routine spine navigation and robotic-assisted procedures. Additionally, we present cases performed with a spinal robotic device, assessing not only the accuracy of the robotic-assisted procedure but also other factors (eg, minimal invasiveness, radiation dosage, and learning curves). Currently, the use of robotics in spinal surgery greatly enhances the application of minimally invasive procedures by increasing accuracy and reducing radiation exposure for patients and surgeons compared with standard procedures. Second-generation hardware and software upgrades of existing devices will enhance workflow and intraoperative setup. As more studies are published in this field, robot-assisted therapies will gain wider acceptance in the near future.

**KEY WORDS:** Accuracy, Neuronavigation, Robotics, Spinal instrumentation

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The field of spinal surgery has advanced rapidly in recent years, and the integration of robotics may represent the next technological step. Robotic-assisted surgeries for simple and complex procedures are now routinely performed in other surgical disciplines such as urology, cardiac surgery, and general surgery.

The application of image-guided robotic assistance to spinal procedures enables surgeons to visualize and navigate complex anatomic structures during the planning and execution stages. These platforms provide critical support for minimally invasive surgical (MIS) procedures while simultaneously improving their accuracy and lowering the incidence of neurological deficits. In many ways, spine surgery is ideally suited for the integration of robotic-assisted surgical procedures. Spine procedures commonly require fine manipulation of critical structures that are often accessed through minimally invasive corridors. The procedures can be quite lengthy and tedious, which can potentially lead to performance fatigue. A robotic interface can significantly improve microsurgical dexterity by dampening physiological tremor and scaling down hand motion.[1,2] Robots are indefatigable and are able to perform repetitious tasks with precision and reproducible outcomes.

**ABBREVIATION: MIS,** minimally invasive surgical

When clinically feasible, MIS procedures are usually preferred over open approaches because they involve shorter convalescence periods, lower infection rates, and more rapid recovery rates, in addition to less pain, blood loss, and tissue trauma.[3-5] However, MIS procedures have been reported to expose surgeons to radiation for durations that are more than twice as long as computed tomography (CT)-based or computer-assisted procedures[6]; for spinal procedures, radiation doses are 10- to 12-fold higher than those measured after nonspinal procedures.[7] Thus, many surgeons still opt for standard open approaches, as clearly illustrated in a retrospective review of 108 419 spinal surgeries conducted during the period of 2004 to 2007 in various medical centers in which only 13.2% were performed using a minimally invasive approach.[8]

Even though robotic technology holds great potential for spinal surgery, it is of utmost importance to establish its practicality and to demonstrate better clinical outcomes compared with traditional techniques, especially in the current cost-effective era. This article includes a short description of robotic structures and workflow, followed by preliminary results of a prospective study comparing conventional, navigation, and robotic procedures. We incorporate cases performed with a spinal robotic device, assessing not only the accuracy of the robotic-assisted procedures but also other factors such as minimal invasiveness, radiation dosage, and learning curves.

## MATERIALS AND METHODS

### Patients

Within a 12-month period, surgeries were performed on 46 patients with 244 robotic-assisted pedicle screws. Reasons for spinal instrumentation included vertebral body fracture, status postspondylodiscitis, and degenerative instability or tumor destruction of the vertebral body. Additionally, beginning in 2010, a consecutive series of patients with monosegmental degenerative lumbar instability have been enrolled in a prospective randomized study with 3 arms: free-hand instrumentation vs standard spinal surface-matching neuronavigation (System BrainLab VectorVision 2, Feldkirchen, Germany) and robotic-assisted navigation (SpineAssist surgical guidance robot; Mazor Robotics, Caesarea, Israel). Outcome analysis was performed for accuracy, time management, and intraoperative radiation dosage. Here, we report our preliminary results of 37 patients.

All patients recruited for this study had to fulfill the following inclusion criteria: age $>$ 18 years, indication for monosegmental lumbar stabilization using a pedicle screw-based internal fixation system, no previous spine surgery at the affected level, no primary spondylolysis, and informed consent to participate in the study. Patients were randomized to conventional fluoroscopy-assisted free-hand pedicle screw placement, standard open surface-matching spinal neuronavigation, or robotic-assisted pedicle screw placement at a 1:1 ratio.

### Robot Setup

SpineAssist is a bone-mounted semiactive (250 g) robot offering surgical tool guidance. It can move its end effector in 6 *df*, eventually locking it into place along the preplanned entry point and trajectory. Its bone-mounting feature allows the system to work in harmony with patient breathing or motion, ensuring a fixed robot position with respect to the patient's vertebrae. The workstation orchestrates the preoperative planning, image acquisition and registration, kinematic calculations, and robot control. A thin-slice preoperative CT scan covering the levels of interest and their flanking levels is performed and then transferred to the surgical preplanning program. This CT scan is reconstructed to form 3-dimensional x-ray images using the system's proprietary software. The software allows interactive planning and optimization of length, diameter, positioning, and trajectories of the implants. The surgical blueprint is then transferred to the workstation in the operating room. A specialized mounting platform (t bar) is then anchored to a rostrally located spinous process with a k wire of the anesthetized patient lying in a prone position. A fiducial array is placed on the mounting platform, and 2 fluoroscopies are taken (anteroposterior plane and 60° oblique to the lateral plane). Using the fiducials, the computer automatically overlays the images on the preoperative CT and registers the surgical blueprint with the physical location of the mounting platform. The fiducial array is then removed, and a robotic guidance arm draped in a sterile sheath is secured to the mounting platform. The robot is dispatched by the surgeon in accordance with the surgical blueprint to provide the trajectory and entry point for the instrumentation (eg, in position to reach and drill through a pedicle). A metal arm is then attached to the robot to hold the drill guide, and the surgeon can now work through it to accurately drill or instrument the target vertebra. This process is repeated until all the vertebrae are instrumented. The robotic device can be moved along the t bar to reach all planned trajectories (Figure 1).

### Surgical Technique

For conventional free-hand pedicle screw implantation, anteroposterior and lateral fluoroscopy (BV Endura; Philips, Eindhoven, Netherlands) was used during the procedure. A midline approach to the spine was established. By the identification of anatomic landmarks and use of lateral and anteroposterior fluoroscopy, pedicle screws were implanted and connected to rods (Tango; Ulrich Medizintechnik, Ulm, Germany). The fluoroscopy was conducted at the discretion of the surgeon inconsistently at certain steps of screw implantation, meaning anteroposterior fluoroscopy only if necessary. A subsequent decompression of the spinal canal and posterolateral fusion procedure with autologous bone was performed in all cases. Percutaneous procedures were performed using the Spine Assist robot as described with implantation of VIPER2 screw/rod-system (DePuySynthes, Warsaw, IN, USA).

The primary end point of the study was the accuracy of the pedicle screws as assessed by a postoperative thin-cut CT scan. Any cortical breaches of the pedicular borders by the screw were measured in millimeters in the medial, lateral, cranial, or caudal direction according to Gertzbein and Robbins.[9] Screw positions were classified as follows: within the pedicle (group A), cortical breach of $<$ 2 mm (group B), cortical breach of $\geq$ 2 but $<$ 4 mm (group C), cortical breach of $\geq$ 4 but $<$ 6 mm (group D), and cortical breach of $\geq$ 6 mm or more (group E; Figure 2). As secondary end points, the duration of the trajectory planning, the duration of the preparation in the operating room, and the radiation exposure were noted. Furthermore, patients' sex, age, and body mass index, levels of instrumentation, number of instrumented levels, calculated accuracy of the CT-fluoroscopy matching, days of postoperative hospitalization, number of screw revisions, and conversions to a free-hand approach in the navigation groups were acquired. The study aimed for randomization of 30 patients per group with 4 screws per patient, resulting in 120 implanted screws per group. Therefore, the results reported here are preliminary without statistical evaluation to describe trends. The local ethics committee approved the study.

## RESULTS

Of 64 patients operated on with the robotic device, the planned robotic procedure could not be executed in 2 patients owing to failure to reach any matching of intraoperative imaging to the preoperative CT scan. The anticipated reason was bad bone quality on intraoperative x-ray or artifacts overlying the region of interest such as a pacemaker cable or sternal wiring from previous cardiac surgery. These patients received a conventional open

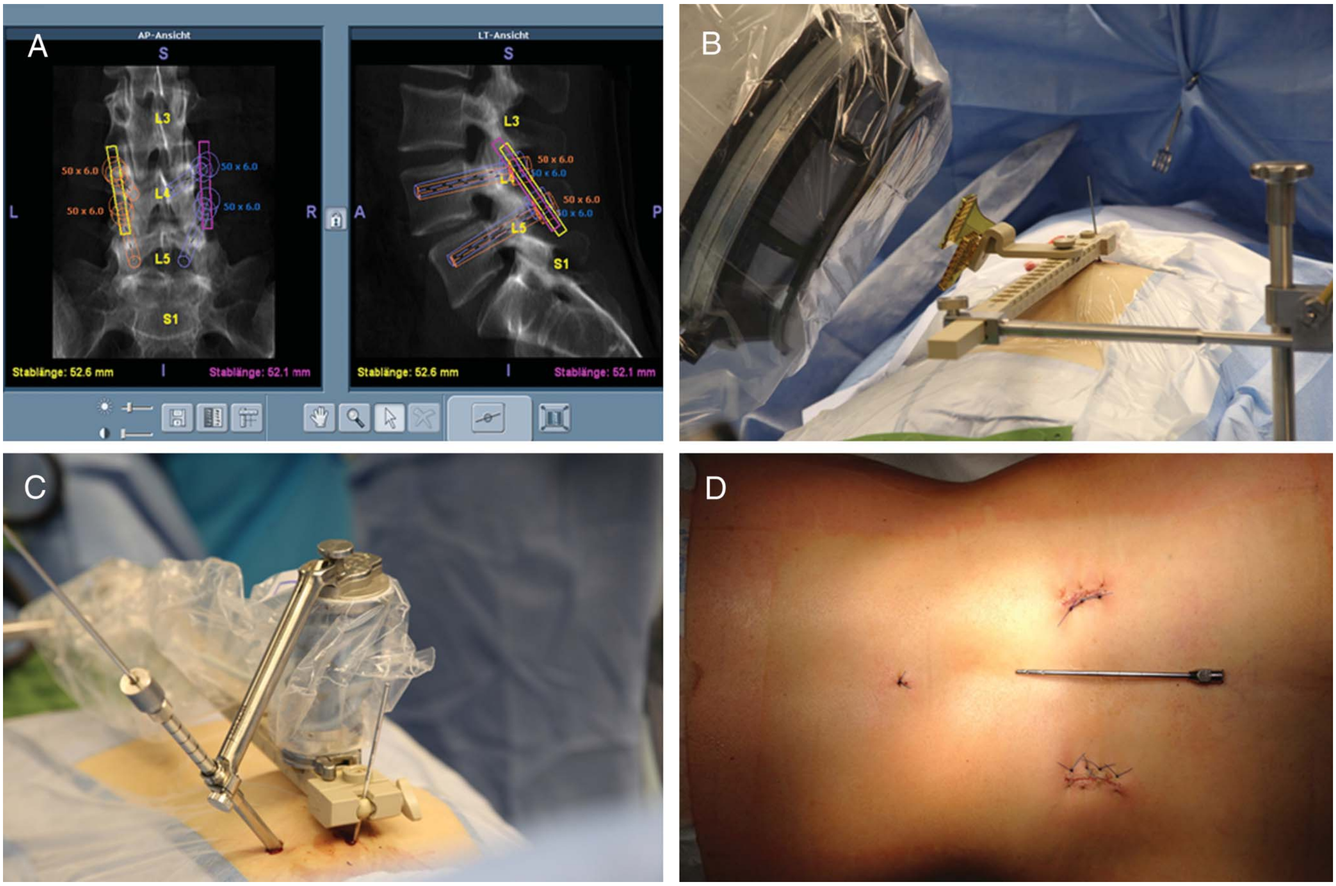

**FIGURE 1.** *SpineAssist setup. Preoperative computed tomography–based planning of the transpedicular screws (**A**); intraoperative oblique fluoroscopy for referencing the SpineAssist robot (**B**); SpineAssist positioned on the bed mount angulating the screw trajectory (**C**); and end of the procedure demonstrating tiny skin incisions for 4 transpedicular screws (**D**).*

procedure. Vertebral bodies from T1 to S1 were involved, with predominance in L2-4 (52% of all screws). Optimal accuracy with pure intrapedicular trajectory according to the Gertzbein and Robbins[9] criteria was 92%, with 5.3% of the screws exhibiting a lateral deviation and 2.5% showing a medial deviation (Figure 3). The patients with medial screw deviations received a surgical revision. Of these patients, 65% (30 of 46) were operated on with a minimally invasive pure percutaneous approach.

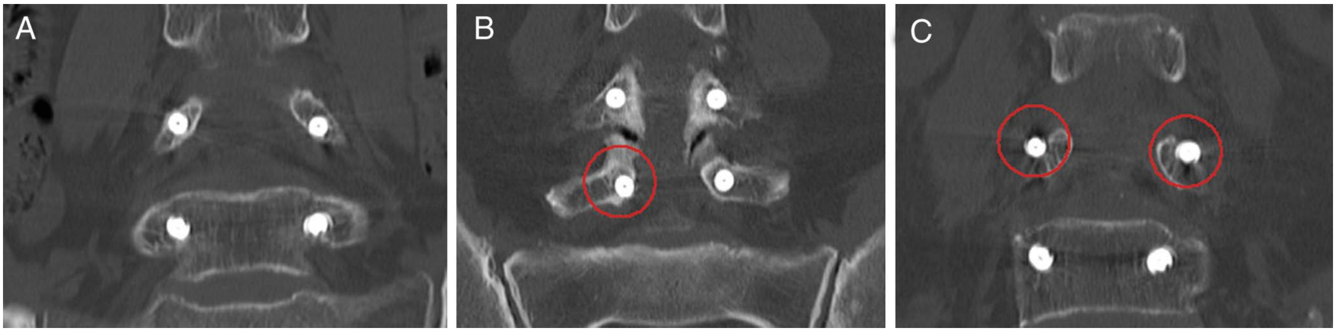

**FIGURE 2.** *Gertzbein-Robbins[9] classification (coronal reformatted postoperative computed tomography scans). Screws exactly within the pedicle were evaluated as group A (**A**); screws deviating $<$ 2 mm, as group B (**B**); screws deviating $\geq$ 2 to $<$ 4 mm, as group C (**C**); screws deviating $\geq$ 4 to $<$ 6 mm, as group D (not shown); and screws deviating $>$ 6 mm, as group E (not shown).*

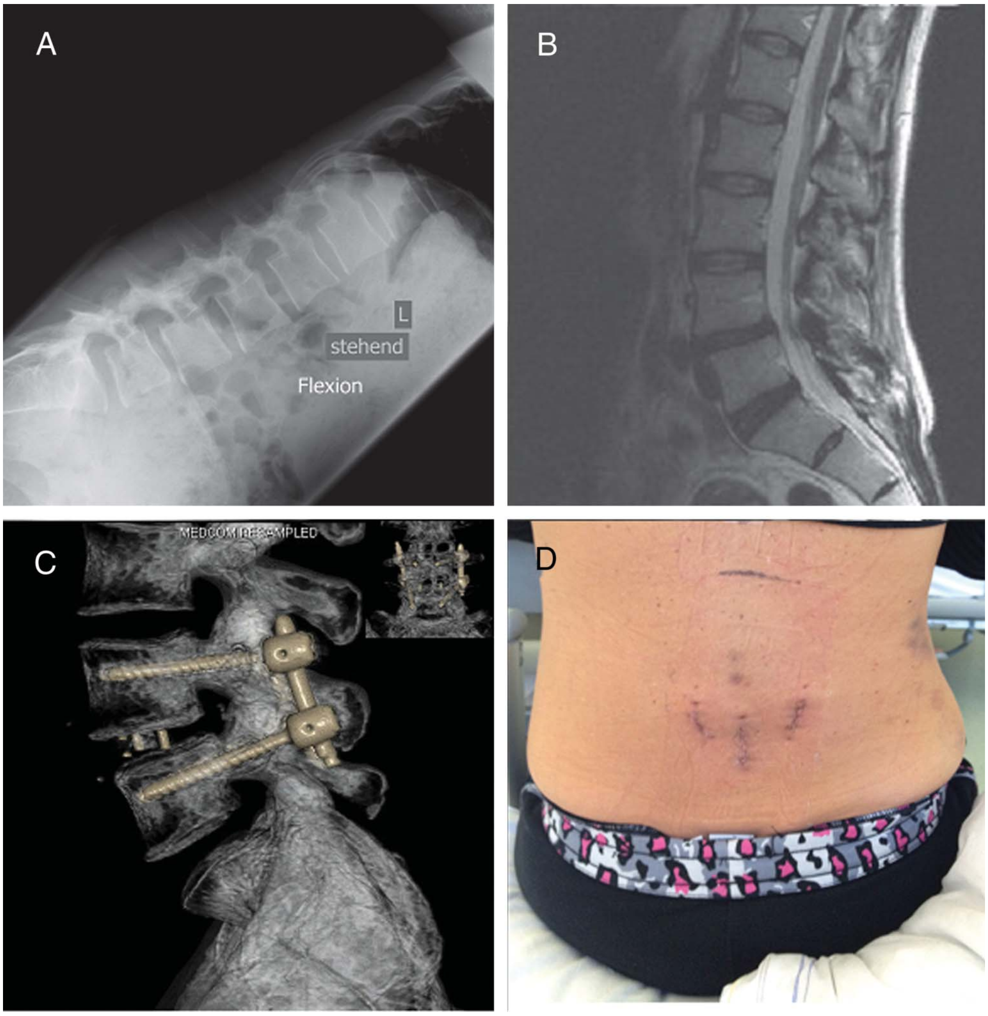

**FIGURE 3.** *Patient operated on with the SpineAssist robot. Preoperative imaging demonstrates degenerative spondylolisthesis L4/5 (***A***) with black disk phenomenon L4/5 in T-weighted magnetic resonance imaging (***B***). Postoperative 3-dimensional computed tomography scan demonstrates perfect screw and transforaminal lumbar interbody fusion position (***C***). Small skin incisions allow percutaneous placement of 4 transpedicular screws and transforaminal lumbar interbody fusion cage (***D***).*

The results of the prospective randomized trial comparing free-hand techniques (n = 10) with navigation (n = 9) and robotic procedures (n = 18) are summarized in the Table. With comparable accuracy and acceptable time elapsed for the navigation procedure, the radiation time and dosage in the navigation and robotic groups were substantially shorter.

## DISCUSSION

The increasing incidence of spinal surgeries has prompted technological developments aimed at overcoming the limitations of MISs and at further enhancing their performance. With the use of conventional techniques, perfect pedicle screw placement depends on selection of the correct insertion point at the posterior cortex of the vertebra being instrumented. This selection is accomplished according to anatomic landmarks and intraoperative fluoroscopy. The pilot hole is placed in a trajectory straight down the axis of the pedicle to the anterior cortex but not penetrating it because nerve roots are in close proximity to its location that is medial and inferior to the bony structure.

Automation and robotics have been applied to a wealth of procedures performed in spine surgery. A meta-analysis published by Kosmopoulos and Schizas[10] determined that of 16 717 pedicle screws placed in the lumbar spine in vivo, 86.7% were accurate. Moreover, the meta-analysis, covering 37 337 pedicle screw implants in total, showed that navigation of pedicle screw implantations improved placement accuracy by a mean of 5% compared with unassisted procedures.

**TABLE.** Results of the Prospective 3-Arm Randomized Study

| | Free-Hand (n = 40 Screws) | Navigation (n = 36 Screws) | Robotic Assisted (n = 72 Screws) |
|---|---|---|---|
| Accuracy, %[a] | 97.5 (Group B, 1 screw) | 92 (Group B, 2 screws; group C, 1 screw) | 99 (Group C, 1 screw) |
| Time management preoperatively (SD), min[b] | . . . | 5.5 (3.5) | 20 (5.3) |
| Time management intraoperatively (SD),[c] min | 27.8 (8.7) | 40.2 (11.4) | 35.2 (11.3) |
| Radiation time (SD), s | 31.5 (11.4) | 10.36 (6.0) | 15.98 (8.6) |
| Radiation dosage (SD), mGy | 18.9 (11.7) | 4.04 (2.9) | 11.03 (10.8) |

[a] According to Gertzbein and Robbins[9] criteria.
[b] Preoperative planning for neuronavigation at workstation.
[c] Start of navigation/pedicle preparation to last screw.

Radiation exposure to the surgeon, patient, and operating room staff can be significant, especially in longer fusions and revision surgeries, in which patients have distorted anatomy and no longer possess regular anatomic landmarks. MIS techniques require even more radiation exposure because landmarks are obscured and can be detected only by fluoroscopy.[11,12] Therefore, errors in placement are a primary concern, with 1 study reporting that almost 10% of patients need revision surgery.[13] An average radiation exposure time of 34 seconds per screw for robotic-guided insertions vs a mean of 77 seconds for conventionally inserted screws has been reported.[14] Schoenmayr and Kim[15] reported a nearly 40% lower median radiation exposure than in conventional pedicle screw insertion techniques when robotic-assisted techniques are used in percutaneous spinal fusion surgery. Similarly, another single-center study demonstrated up to 70% lower radiation exposure in SpineAssist-guided than in conventional procedures.[16] That the radiation exposure for robotic-assisted surgeries in our study is less than that in free-hand procedures but still more than with conventional navigation techniques can be explained by the learning curve of the new robotic technique and the fact that spinal navigation has been performed on a daily basis in our department since 2004.

In recent years, a variety of robots for different surgical applications have been introduced.[17] Nathoo et al[18] classified surgical robots into 3 broad categories: (1) supervisory-controlled systems in which the surgeon plans the operation offline, specifying the motions that the robot must follow to perform the operation, and the robot then performs the procedure autonomously with the surgeon closely supervising; (2) telesurgical systems that allow the surgeon to directly control the surgical instruments held by the robot via a joystick or hand controls in which task execution can be either passive or active; and (3) shared-control systems that allow both the surgeon and the robot to directly control the surgical instrument at the same time. To date, the majority of robotic-assisted spine operations have involved a shared-control system. This system has generally involved the robotic arm moving an instrument holder to a predetermined location based on cartesian coordinates and then being locked into place. The surgeon then directs the instrument along the path defined by the robot. This technique has been used successfully in stereotactic procedures,[19] endoscopy,[20] and spinal pedicle screw placement.[21]

Nevertheless, published experiences have come to the conclusion that the more the surgeon is involved in the surgical workflow, the more likely it is that robot-assisted therapies will gain acceptance.[21] Taking this result into account for spinal procedures, the ideal surgical robot should work semiautonomously (ie, it would control the alignment of the surgical instrument by means of intraoperative navigation according to patient-specific planning). The surgeon would take over the guidance of the robot by means of haptic interaction along trajectories to the target area (so-called hands-on robotics) and would thus keep full control over the operative process. The combination of robot and navigation system is an important step in closing the gap in the flow of information between therapy planning and therapy execution. With such a combination, the data gained from navigation can be optimally and directly integrated into the therapy.

Introduced in the 1990s, spinal surgical robotic systems have significantly increased the surgeon's capacity to perform MIS procedures accurately in a variety of clinical applications. The reproducibility, precision, and accuracy of their movements have enabled robots to perform some surgical tasks more precisely than their human counterparts. A few robotic systems have spinal applications. The Miro system was developed at the German Aerospace Centre DLR, and a possible setup for pedicle screw placement was investigated.[22] The system consists of a lightweight robotic arm, an optical tracking system, and software. In the operating room, several robot control modes adapted to surgical requirements are available. In the final step, the surgeon uses a drill held by a passive drill holder positioned by the robot. The Cooperative Robotic Assistant is a kinematically closed structure and a new drill-by-wire mechanism for placing screws.[23] The surgeon teleoperates the robot using a haptic device with a single degree of freedom. At the moment, no external tracking is integrated into this system. The capabilities of the da Vinci system have been highlighted, and its limitations have been clarified in several animal[24-26] and human studies.[27,28] It has been implemented in the performance of anterior lumbar interbody fusion with the retroperitoneal approach and in laminotomy, laminectomy, disk incision, and dural suturing procedures on the thoracolumbar spine of a porcine model in vivo.[24,25] In humans, this platform was involved in robot-assisted transoral odontoidectomy for decompression of the craniocervical junction.[27] The Georgetown robot (Johns Hopkins University, Baltimore, MD), introduced in 2002 and developed as a percutaneous needle driver for minimally invasive spine procedures, was designed for an interventional suite under biplane fluoroscopic guidance; the robot arm, which is mounted on the scanner table, has 6 *df*.[29]

The robotic device used in this report represents the described hands-on robot. It consists of a compact robot attached to the spine with a base platform and a workstation for planning and navigation. Registration is based on matching of preoperative CT scans and intraoperative fluoroscopic images acquired with a calibrated device.[21] The robot is attached to an instrument guide through which the surgeon executes the drilling along the trajectory for screw placement without any interference. With this concept, the SpineAssist is applicable not only for spinal instrumentation but also for targeting biopsies, extraforaminal disk prolapses in distorted anatomic spaces, or arteriovenous fistulas with obscured vascular entry points into the spinal canal.

In a retrospective 14-center study evaluating the 3271 spinal implants inserted under SpineAssist guidance, clinical acceptance rates reached 98.3%, with no reports of irreversible nerve damage.[3] When the 646 pedicle screws postoperatively assessed by CT imaging are considered, 98.3% met the class A or B Gertzbein and Robbins[9] criteria, with a mean deviation of 1.2 ± 1.49 and 1.1 ± 1.15 mm on the axial and sagittal planes. In addition, 49% of the reviewed cases were performed with a percutaneous approach despite the anatomic complexity presented. One reason for the higher rate of minimally invasive procedures was the clear advantage of the system in percutaneous and minimally invasive approaches, wherein SpineAssist guided the surgeon to the precise location without needing to see the anatomy.[14] Thus, in open regular cases in which the anatomy is clearly seen, the advantage is less significant for the surgeons. In deformity cases, visualization of surface anatomy alone may not be sufficient, and robotic guidance can be advantageous. This is especially relevant to the concave vertebral scoliosis pedicles along the apex of a large curve because pedicles are deformed. Using SpineAssist in percutaneous cases provides additional advantages: The capacity to optimally locate the entry point at the skin level minimizes incision size and radiation exposure.[11] In an article by Schizas et al,[30] the accuracy of pedicle screw insertion through the percutaneous approach was investigated with postoperative CT scans. With the use of the Wiesner et al[31] criterion, it was found that in the coronal view (axial view), 30% (23.3%) of the screws breached the pedicle cortical wall with 21.7% (20%) encroachment, 5% of the screws had minor breaching ($<$ 3 mm), and 3.3% (3.3%) had severe breaching ($>$ 6 mm). According to these authors, this accuracy rate was considered acceptable because it largely fell within the limits of the open procedure misplacement rate. However, future studies with the robotic device have to be in competition with the best available imaging such as intraoperative CT scanners. These ultramodern installations spare preoperative and postoperative imaging and dramatically decrease the rate of reoperations and the radiation exposure to the patient and staff.[32] However, the decision to invest in a CT scanner devoted solely to spine surgery has to be considered wisely.

The advantages of robotic surgery include ergonomics,[27] significant dexterity enhancement that eliminates the neurosurgeon's physiological tremor,[24,26] reduction of radiation exposure, image-based semiactive guidance for inserting implants, excellent 3-dimensional visualization,[27] the capacity for repetitive motions and holding tools for long periods, small skin incisions,[13,15] minimal paravertebral muscle dissection, minimal retraction,[24] and minimal bleeding and infection.[24,26] However, how does a robotic system differ from well-established navigational systems? Because the device is fixed on the patient's spine and because referencing is based on fluoroscopy without surface matching of the planned vertebrae, a percutaneous navigation is amendable. With all other procedures, the robotic device is in competition with established surface-matching navigation systems. However, the use of the robotic device in a percutaneous procedure is a great advantage, given that minimally invasive procedures will increase in the future as data on the improved outcomes of such surgeries continue to be published in the literature. Furthermore, the industry provides the surgeon with an armamentarium of percutaneous minimally invasive spinal instrumentations.

Advancement is made when a new technology adds value to some important aspects for patients, eg, improved outcome, improved efficiency, more cost-effectiveness. Although the robotic procedures proved to save radiation time in our preliminary data of the comparative study, they still consume more exposure time than with conventional navigation techniques. The true value of the robotic-assisted surgeries becomes apparent in the evaluation of percutaneous procedures in which radiation exposure of free-hand techniques increases dramatically, standard navigation techniques are not applicable, and robotic-assisted procedures do not require any more radiation time than open procedures. However, any devices or tools used to guide the spine surgeon will consume time and resources, as shown in the Table.

This technology is even more relevant to procedures of the cervical spine in which the need for precision is crucial. There is a much smaller target bone volume; the vertebral arteries are intimately related to the vertebral bone complex; and the cervical spinal cord and nerve roots are in close proximity. Robots also need to be adapted to the limited surgical access in the cervical spine (neck). Neurological complications have been reported to be up to 3.7% for instrumentation of the second cervical vertebra, with an incidence of arterial injury of 4.1% to 8.2% and an optimal screw placement of only 68.7%. The newest generation of the SpineAssist robot has been adapted for cervical cases, and the first surgeries have been performed with promising results, making percutaneous procedures of the cervical spine conceivable. Nevertheless, new technologies imply learning curves even for experienced spine surgeons who have to rely on possibly unusual robotic-forced trajectories. Failures during planning, referencing, adjustment of the robot, or drilling execution might potentiate to an inferior outcome compared with fast-forward free-hand procedures. With wider acceptance and application of robotic techniques, execution and software processes might become more intuitive and easier to apply, becoming a real superior partner to the spine surgeon.

## Outlook

Although the use of robotics in surgery is in its infancy, we believe that the few surgical robots performing currently in operating rooms have already shown great potential to improve surgical outcomes, especially when accuracy and minimal invasiveness are needed. However, current systems are extremely expensive, are large, and typically require immobilization of the patient.[17] Moreover, the equipment requires carbon surgical tables so as not to interfere with the referencing process. The learning curve has to be taken into consideration; the registration process could lead to systemic errors before execution of the procedure. Again, safety is a big issue because computer-controlled surgical robotics may be associated with inadvertent motion. A robot device should be ideally universal in its use, not just designed specifically for the spine but capable of various procedures to create a joint venture among surgical disciplines.

## Disclosure

The authors have no personal financial or institutional interest in any of the drugs, materials, or devices described in this article.

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