Spine surgery has experienced much technological innovation over the past several decades. The field has seen advancements in operative techniques, implants and biologics, and equipment such as computer-assisted navigation and surgical robotics. With the arrival of real-time image guidance and navigation capabilities along with the computing ability to process and reconstruct these data into an interactive three-dimensional spinal “map,” so too have the applications of surgical robotic technology advanced. While spinal robotics and navigation represent promising potential for improving modern spinal surgery, it remains paramount to demonstrate its superiority as compared to traditional techniques prior to assimilation of its use amongst surgeons.

The applications for intraoperative navigation and image-guided robotics have expanded to surgical resection of spinal column and intradural tumors, revision procedures on arthrodesed spines, and deformity cases with distorted anatomy. Additionally, these platforms may mitigate much of the harmful radiation exposure in minimally invasive surgery to which the patient, surgeon, and ancillary operating room staff are subjected. Spine surgery relies upon meticulous fine motor skills to manipulate neural elements and a steady hand while doing so, often exploiting small working corridors utilizing exposures that minimize collateral damage. Additionally, the procedures may be long and arduous, predisposing the surgeon to both mental and physical fatigue. In light of these characteristics, spine surgery may actually be an ideal candidate for the integration of navigation and robotic-assisted procedures. With this paper, we aim to critically evaluate the current literature and explore the options available for intraoperative navigation and robotic-assisted spine surgery.

KEY WORDS: CT-based navigation, Mazor, Navigation, Pedicle screw, Robotics, ROSA, Spinal robotics, Spine assist

ABBREVIATIONS: ALIF, anterior lumbar interbody fusion; CAN, computer-assisted navigation; FDA, Food and Drug Administration; FH, free hand; ioUS, intraoperative ultrasound; MIS, minimally invasive surgery; MRI, magnetic resonance imaging; OR, operating room; 3-D, three-dimensional
By definition, robots do not fatigue and the Ziehm Vision FD Vario 3-D with NaviPort allows for pivoting of the table after scanning and registration (Figure 3). The patient is anesthetized and intubated on a gurney and then transferred to the operating room. The OR staff are subjected to harmful radiation exposure in minimally invasive surgery (MIS) procedures on arthrodesed spines, and deformity cases with distorted anatomy. Additionally, these platforms may mitigate much of the harmful radiation exposure in minimally invasive surgery (MIS) to which the patient, surgeon, and ancillary operating room (OR) may be long and arduous, predisposing the surgeon to both mental and physical fatigue. In light of these characteristics, spine surgery may actually be an ideal candidate for the integration of navigation and robotic-assisted procedures. These platforms have been shown to dramatically improve a surgeon’s manual dexterity allowing for greater control and maneuverability through a less invasive working portal, while dampening a surgeon’s physiological tremor. By definition, robots do not fatigue and are capable of performing repetitive tasks with accuracy and precision, yielding infinitely reproducible outcomes.

Robotic-assisted surgery has been used for years by other surgical subspecialties. The robots come in a variety of designs with varying levels of “assistance” that can be broken down into 3 broad categories: (1) supervisory-controlled systems whereby the machine is programmed with predetermined actions that are carried out with robotic autonomy and close surgeon supervision; (2) telesurgical systems, like the Da Vinci robot (Intuitive Surgical, Sunnyvale, California), that afford the surgeon complete control of the motions of the machine from a remote command station; and (3) shared-control models, a form of co-autonomy allowing both the surgeon and robot to simultaneously control motions. With this paper, we aim to critically evaluate the current literature and explore the options available for intraoperative navigation and robotic-assisted spine surgery.

3-Dimensional CAN Options

Many platforms are currently available for use in the field of spine surgery. We will review some of the intricacies and technology specifications of the Airo Mobile Intraoperative computer tomography (CT)-based Spinal Navigation (Brainlab®, Feldkirchen, Germany), Stryker Spinal Navigation with SpineMask® Tracker and SpineMap Software (Stryker®, Kalamazoo, Michigan), Stealth Station Spine Surgery Imaging and Surgical Navigation with O-arm (Medtronic®, Minneapolis, Minnesota), and Ziehm Vision FD Vario 3-D with NaviPort integration (Ziehm Imaging®, Orlando, Florida).

The Airo Mobile Intraoperative CT-based CAN platform (Brainlab®) was approved for use in the US by the Food and Drug Administration (FDA) in October, 2013. The technology is one of the pioneers of the navigation platforms and has many similarities to other CAN systems. Some differences in the platform include its mobility and larger diameter of scanner than other manufacturer’s scanner. The circular scanner is attached to the operating table and allows for full 360° scanning. Additionally, the entire unit is mobile as well as the attached OR table that allows for pivoting of the table after scanning and registration (Figure 1). The patient is anesthetized and intubated on a gurney and then transferred to the operating room. The instruments to be used in the surgery have 3 attached reference points that are recognized by the system’s scanning stereotactic camera (Figure 2). These instruments may be calibrated during the anesthesitization process, during prepping and draping, or during spinal exposure in the open cases. Prior to intraoperative CT scanning, an anatomic reference clamp is attached to a spinal process that allows registration of the CT image with the same camera used for the instrument registration (Figure 3). An alternative option, mainly for percutaneous cases, is to place 2 reference pins in the iliac crest. The patient is then put through the scanner and a full 32-slice CT scan is obtained. Importantly, the OR staff, aside from the anesthesiologist who is wearing lead and moved away from the scanner, exit the room during the scanning process to avoid undue radiation exposure. Once the image is obtained, it is automatically registered to the Brainlab® software, which generates a real-time 3-D map that is registered with the precalibrated instruments allowing for stereotactic guidance of instrumentation. The diameter of the scanner measures 107 cm, which is larger than the other scanners such as the Ziehm Vision FD Vario (89 cm; Ziehm Imaging®).

The Stealth Station with O-arm (Medtronic®) and the Ziehm Vision FD Vario 3-D utilize very similar technology for spinal CAN. The O-arm is also a 360° scanner, but opens at 90° to allow for mobilization around the patient. The Ziehm Vision FD Vario 3-D is a C-arm-based technology that acquires its images via a 190° rotation about the patient. The data are then reformatted to produce a 360° 3-D map of the patient’s anatomy. Both systems rely on the scanning camera for instrument registration and real-time navigation. A drawback to this form of registration, however, is as the case with the Airo Mobile system (Brainlab®), is the reference clamp that are placed on the spine must not be touched, as this will alter the registration process and lead to errors in stereotaxis as the “map” has now shifted relative to the instruments in space. In the event that the reference clamp is inadvertently bumped or moved, the patient must be rescanned to provide a new spinal map for accurate navigation.

The Stryker SpineMask® Tracker sought to mitigate these concerns by providing a different form of reference. This system relies on a rectangle of trackers that is applied directly on to the patient (Figure 4). This referencing system negates the possibility of reference point translation and allows the surgeon to...
work free of obstacles. The novel design is not without its own peculiarities though. The camera must have full view, clear of obstruction to 5 of the 31 LEDs that are actively tracking. This means that a surgeon’s arm or body resting on the patient must not obstruct more than half of the reference points of the rectangle tracker. Additionally, the operative field cannot extend beyond the predefined size parameters of the rectangular reference points. Additionally, undue skin tension or movement, such as what might be encountered with large vertical incisions and deep retraction, may alter the reference point location, effectively altering the 3-D computer-generated spinal map. For these reasons, this SpineMask© Tracker (Stryker) seems well suited for minimally invasive percutaneous procedures, but may be less accommodating for larger, open procedures involving many segments of the spine.

Safety and Applications of Intraoperative Navigation

The application of CT-based 3-D navigation in spine surgery has been well studied with over 20 clinical trials utilizing various manufacturers’ platforms.6–34 Primary end points in the majority of studies have evaluated the accuracy and safety of pedicle screw placement utilizing this technology. In addition, several meta-analyses and systematic reviews have attempted to resolve the clinical equipoise surrounding CAN techniques.35–39 However, even with a critical mass of data on well over 10,000 pedicle screws, many still interpret the literature as equivocal. This likely has as much to do with the well-documented success rates and safety profile of free-hand (FH) pedicle screw instrumentation as it does with the evolving technological limitations of the many different platforms for CAN that may add significant heterogeneity to results.
Schwarzenbach et al.\(^2\) first published on the accuracy of pedicle screw placement utilizing a novel CT-based navigation system. They found a rate of 2.7% pedicle breach in 162 lumbar pedicle screws placed in vivo. The authors also commented on the learning curve of the CAN, noting more breaches in the earlier utilizations of the technology. Not long after that in 2000, Amiot et al.\(^6\) conducted a similar study, though they added a control arm of FH conventional pedicle screw instrumentation for comparison. In their cohort trial, they found an error rate of 15.3% for 544 screws from T5 to S1 for the FH technique, while only 5.4% for the 294 screws inserted utilizing CAN.\(^5\) Seven of the patients in the FH cohort necessitated reoperation and 4 patients sustained long-term neurological sequelae, whereas no patients required reoperation in the CAN group and none experienced postoperative neurological deficits. The authors concluded that CAN was a valuable tool to increase accuracy and safety of pedicle screw instrumentation. In the largest single in vivo study to date, Yu et al.\(^25\) evaluated the accuracy of 2062 thoracic and lumbar pedicle screws utilizing intraoperative 3-D imaging and found only 4.6% to be breached >2 mm compared to 16% in 276 FH screws (\(P < .001\)). The authors additionally found a significantly decreased rate of operative time in the navigation cohort and concluded that 3-D navigation-assisted screw instrumentation was more accurate and less time consuming than conventional FH techniques.

The mass of data relevant to the topic of pedicle screw accuracy and safety of implantation is ideal for meta-analysis comparison. Verma et al.\(^37\) conducted the first of several meta-analyses on the topic including 23 studies, seen in Table 1, evaluating 5992 pedicle screws and found a significantly higher rate of accuracy utilizing CAN. However, though the rate of neurological injury favored navigation, the group failed to demonstrate statistical significance (\(P = .07\)). The findings of a later meta-analysis performed by Shin et al in 2012\(^39\) echoed these results. The authors found the overall incidence of breach using CAN...
techniques to be 6% as compared to 15% for FH technique when evaluating over 7000 pooled pedicle screws (Table 2). Additionally, the authors performed subanalyses of cervical, thoracic, and lumbar pedicle screws and reported significantly more accurate screw placement for all 3 spinal segments utilizing navigation. They too, however, failed to demonstrate a significant difference in reoperation rates between the 2 techniques. Results of these 2 large meta-analyses confer the notion that although CAN may reduce pedicle screw breach, it has no clinical significance in terms of neurological injury. In the same year, Gelalis et al. reviewed 26 studies and 6617 pedicle screws inserted FH, with fluoroscopic guidance or with CAN. While they found no significance between the fluoroscopic and navigation-assisted methods, both exhibited statistically superior accuracy as compared to FH technique. Again, these authors failed to demonstrate a significantly lower rate of screw revision or total reoperation rates and no difference in neurological injury. In the most recent meta-analysis, Shin et al. used stringent exclusion criteria, including exclusion of noncomparative studies using differing platforms for navigation guidance, studies without explicit complication data, and studies examining cervical pedicle screws resulting in only 12 studies evaluating 4953 screws. They too demonstrated significantly increased screw accuracy with CAN. Perhaps due to their strict inclusion criteria, they also reported a significantly lower rate of screw-related complications in the navigation cohort as compared to FH ($P = .008$).

**CAN for Surgical Resection of Tumors**

While pedicle screw instrumentation has garnered much of the focus of CAN techniques in spine surgery, resection of spinal tumors remains a relatively underexplored utility of this technology. This application of CAN was borne out of modification of its well-documented use in base of skull pathology. In the late 1980s, Roberts et al. described the first frameless stereotactic CAN system, designed to target primary tumors of the brain and skull base. Since their seminal paper, technological advances have enabled this originally primitive platform to now address more challenging pathology of the neuraxial spine, including primary spinal column tumors as well as intradural tumors.

In the first study utilizing CAN guidance for tumor excision of thoracic spine, Arand et al. demonstrated the potential of this tool as they successfully localized and resected tumors of 12 patients with compressive benign lesions of the thoracic
spine. They reported promising results of this small experimental cohort with symptomatic improvement in all patients and confirmed removal of all offending tumor based on postoperative imaging. They concluded that this form of stereotactic intraoperative navigation was a safe and effective way to resect primary compressive tumors of the thoracic spine from a posterior approach. Rajasekaran et al.\(^\text{43}\) expanded the indications of 3-D navigation to excision of symptomatic osteoid osteomas of the cervical and thoracic spine. The authors described their technique of utilizing CAN to excise 2 cervical and 2 thoracic osteoid osteomas with excellent results, alleviation of symptoms, no complications, and postoperative imaging confirming complete intralesional excision. They concluded that this technology afforded them with a more accurate localization of tumor through a minimally invasive corridor that allowed more preservation of bone, thus maintaining stability without necessitating fusion or instrumentation. Van Royen et al.\(^\text{44}\) echoed these results in their paper reporting on osteoid osteoma excision of the thoracic and lumbar spine in 5 patients. They too found CAN to be a safe means of guided excision with a high-speed burr, with all patients experiencing complete resolution of symptoms, noting postoperative imaging and histological examination demonstrating complete eradication of the lesions with no complications and no recurrence up to 3 years follow-up.

In 2010, Smitherman et al.\(^\text{45}\) described a 4-level en bloc sagittal resection of a giant cell tumor of the chest wall and thoracic spine. The surgeons performed the procedure in a staged fashion, first mobilizing the cord and osseous spine with facetectomies and thoracic nerve root ligations. This portion was performed via a traditional posterior approach. CAN was instrumental to the second stage of the procedure as sagittal hemicorpectomies were performed via stereotactic guidance. Using this technique, the authors successfully resected the tumor en bloc from T4 to T8. This case highlights a novel utility of CAN as the surgeons were able to safely resect a large portion of thoracic vertebra with precise and accurate cuts made utilizing real-time stereotactic feedback. This technique allowed for complete resection with clear margins while avoiding violation of the tumor capsule.
TABLE 2. Publications Used in Meta-analysis by Shin et al.

<table>
<thead>
<tr>
<th>Lead author/year of publication</th>
<th>Type of study</th>
<th>Anatomic area</th>
<th>Navigation modality</th>
<th>Number of pedicle screws</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ishikawa (2010)</td>
<td>Case control</td>
<td>Cervical</td>
<td>2-D</td>
<td>276</td>
</tr>
<tr>
<td>Han (2010)</td>
<td>Case control</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>176</td>
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<td>Thoracolumbar</td>
<td>3-D</td>
<td>375</td>
</tr>
<tr>
<td>Nakashima (2009)</td>
<td>Case control</td>
<td>Lumbar</td>
<td>2-D</td>
<td>300</td>
</tr>
<tr>
<td>Sakai (2008)</td>
<td>Case control</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>478</td>
</tr>
<tr>
<td>Yu (2008)</td>
<td>Case control</td>
<td>Lumbar</td>
<td>2-D</td>
<td>2338</td>
</tr>
<tr>
<td>Merloz (2007)</td>
<td>Case control</td>
<td>Thoracolumbar</td>
<td>2-D</td>
<td>176</td>
</tr>
<tr>
<td>Kotani (2007)</td>
<td>Case control</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>138</td>
</tr>
<tr>
<td>Lee (2007)</td>
<td>Case control</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>131</td>
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<tr>
<td>Rajasekaran (2007)</td>
<td>RCT</td>
<td>Thoracic</td>
<td>3-D</td>
<td>478</td>
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<tr>
<td>Ito (2007)</td>
<td>Case control</td>
<td>Cervical</td>
<td>3-D</td>
<td>52</td>
</tr>
<tr>
<td>Tian (2006)</td>
<td>Case control</td>
<td>Cervical</td>
<td>3-D</td>
<td>332</td>
</tr>
<tr>
<td>Liu (2005)</td>
<td>Case control</td>
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<td>3-D</td>
<td>304</td>
</tr>
<tr>
<td>Richter (2005)</td>
<td>Case control</td>
<td>Cervical</td>
<td>3-D</td>
<td>260</td>
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<tr>
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<td>Case series</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>60</td>
</tr>
<tr>
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<td>Thoracolumbar</td>
<td>3-D</td>
<td>324</td>
</tr>
<tr>
<td>Arand (2001)</td>
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<td>158</td>
</tr>
<tr>
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<td>Thoracolumbar</td>
<td>3-D</td>
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<tr>
<td>Amiot (2000)</td>
<td>Case series</td>
<td>Thoracolumbar</td>
<td>3-D</td>
<td>838</td>
</tr>
</tbody>
</table>

RCT: randomized controlled trial.

or iatrogenic injury to adjacent vital neural, vascular, and parietal structures.

While its technology predates CAN, intraoperative ultrasound (ioUS) was once the mainstay of neurosurgical real-time image guidance particularly for intradural tumors. With the advances in the field of navigation, ioUS was largely relegated to centers without the technological means for CT-based stereotactic tumor excision. However, recently with improved image quality and computing ability, ioUS has resurfaced in the conversation of advanced navigation techniques for spinal tumors. Though little data exist in the literature, ioUS is currently used as an adjunct for extradural and intradural tumor resection. In 1 recent study, Prada et al. demonstrated that both extramedullary intradural as well as intramedullary spinal tumors could be accurately localized utilizing ioUS. Furthermore, in all 34 patients involved in the study, the full extent of the tumor was accurately visualized intraoperatively. Additionally, the authors found that planned bony resection was altered in 9 of the 34 patients, with a decreased exposure necessitating a shorter instrumented fusion in 8 patients. The authors concluded that ioUS represents a safe, effective, and economic tool that affords the surgeon real-time dynamic image navigation capabilities for the excision of complex extradural and intradural spinal tumors.

Though the bulk of literature pertinent to the topic of spinal tumor excision utilizing intraoperative navigation deals with primary bone tumors, its application may be broadened to soft-tissue pathology. D’Andrea et al. recently reported on a technique that integrates magnetic resonance imaging (MRI) to CAN via coregistration of imaging modalities. This technique involves the “merging” of soft tissue defining MRI images with real-time stereotactic navigation techniques to create a navigable canvas for safe tumor excision. By coregistering images, the authors were able to define soft-tissue tumor borders and adjacent anatomy, including vascular structures and neural elements, facilitating safe excision of primary cervical chordoma, aneurysmal bone cyst, synovial cell sarcoma, and osteosarcoma. The authors concluded that MRI/CT-navigation coregistration techniques have immense potential for use in resection of complex spinal tumors, allowing detailed visualization of osseous and soft-tissue structures.

Intraoperative MRI or MRI/CT Coregistration CAN

Leksell et al. first described the technique of stereotactic surgery utilizing MRI in 1985 for use during localization of deep brain tumors. This novel technique allowed surgeons to visualize, real-time, the intricate parenchyma of the brain with clear distinction of white and gray matter, ventricular anatomy, and deep brain pathology. Their technique utilized a 0.5-Tesla magnet to produce real-time imaging for stereotactic surgery which utilizes an aluminum headring. A decade later, Cohen et al. reported on their clinical results using coregistration of CT and MRI modalities. They compared the accuracy of their novel coregistration techniques to those of independent MR and CT alone and found that coregistration of CT/MRI resulted in a statistically significant decrease in error, measured in mm, in all
3 planes of view. This technology has since been used for functional neurosurgery, primarily in form of thalamotomy, placement of deep brain stimulators, and brain and spinal tumor resection as previously described.59-61

Kamogawa et al62 first sought to apply CT/MRI coregistration technology to spinal pathology at the craniovertebral junction in 2009 case report. In following years, the application of 3-D coregistration technology was broadened to visualize both neural elements and bony structures of the cervical, thoracic, and lumbar spine with great success and fine detail. Most recently, Kamagawa et al63 utilized coregistered images to identify the exact location of cervical nerve root impingement. They presented 4 cases whereby MRI and CT images were merged, easing identification of subtle nerve root compression due to uncovertebral osteophyte. While these images were only used in the preoperative planning setting, they successfully demonstrated the power and potential of the technology. To date, only D’Andrea et al,56 as discussed in the previous section, have reported utilization of CT/MRI coregistration for use in CAN pertaining to the spine.56 More research into this novel CAN technology may provide surgeons with the ability to better visualize the intimate relationship of bony and neural elements real-time in the OR.

Efficiency in the OR and Outcomes

While many studies have demonstrated improved accuracy of pedicle screw instrumentation utilizing CAN techniques, there is a shortage of literature reporting on patient outcomes. Perhaps with greater accuracy and precision of instrumentation comes fewer complications and improved outcomes, though this inference is largely an assumption due to lack of existing data. The success of a spinal fusion procedure depends on many more variables aside from pedicle screw instrumentation, and there is still much clinical equipoise regarding the translation of increased instrumentation accuracy to improved clinical outcomes.

The reported rate of pedicle screw misplacement can be as high as 20% to 40% based on historical data. However, even in studies with such high rates of misplaced screws, only a fraction of patients experience neurological-, visceral-, or vascular-related complications.64-66 Wiesner et al67 reported on 408 percutaneously placed lumbosacral pedicle screws and found 27 instances of screw malposition. However, of those 27 misplaced screws, only 1 was found to cause a neurological complication. This salient point that differences in pedicle screw accuracy, such as that seen in FH, fluoroscopic guided, and CAN, are not associated with clinical significance has been reproduced in the literature with convincing power.6,11-13 This may not be surprising as the neural elements of the lumbosacral spine tend to be more forgiving due to their increased mobility as compared to cord-level neural structures, in which there is less room for error. Therefore, the increased accuracy of CAN pedicle screw placement may translate into improved safety to a larger degree in the cervical and thoracic spine.

In a large series, Richter et al19 compared cervical pedicle screw instrumentation utilizing a conventional FH technique vs CAN and found 8 of 93 (8.6%) screws misplaced by 2 to 4 mm compared to 5 of 167 (3%), respectively. However, none of the 13 malpositioned screws resulted in neurological or vascular injury. Additionally, they found the navigation technique to be more efficient with a mean operating time of 135 min compared to 163.5 min for the FH group. In another large cervical pedicle screw study comparing FH techniques to CAN, Kotani et al11 found a significantly lower rate of pedicle breach in the navigated cohort as compared to the FH instrumentation group. They reported 1/78 (1.3%) malpositioned navigated screws compared to 45/669 (6.8%) in the traditional instrumentation group. Additionally, 2 of the 45 breached screws from the manually inserted group necessitated removal due to neurological deficit, whereas the single malpositioned screw in the navigation group did not have any negative clinical impact. Several other studies have demonstrated the reproducibility of CAN techniques for cervical pedicle screw placement as well as its superiority to traditional techniques in terms of accuracy, though they failed to comment on complications or outcomes.10,14,68,69 Demonstration of safety and efficacy of cervical pedicle screw instrumentation with navigation technology may increase this form of stabilization, as biomechanical studies have shown its superiority of construct strength as compared to the more oft selected technique of lateral mass screw fixation.70,71

Studies evaluating CAN for thoracic screw placement have yielded similar results. Han et al86 conducted a prospective randomized trial evaluating 92 thoracic screws placed with CAN compared to 84 placed under traditional fluoroscopic guidance and found no cortical violations in the navigated group compared to 14 in the fluoro group. The authors also commented on complications with 2 of the 14 breach screws resulting in neurological deficit necessitating removal. They also showed a significant increase in efficiency of navigation-guided screw placement over fluoro with an average of 2.54 vs 4.56 min per screw, respectively (P < .001). Allam et al72 echoed these results in their study comparing navigation to FH thoracic pedicle screw instrumentation in 100 and 108 screws, respectively. They found only 1 (1%) screw malpositioned under the navigation technique compared to 11 (10.2%) in the FH group. Additionally, of the 11 malpositioned screws in the FH cohort, 6 (5.6%) required repositioning of hardware. These results echo those of Kim et al40 in their landmark paper that sought to determine whether or not CAN technique is safe for thoracic pedicle screw instrumentation.40 Their rate of hardware malposition after 3204 FH pedicle screws was 7.9%, though none of the 3204 screws resulted in any neurological, vascular, or other screw-related complication within a 10-year follow-up. Finally, in a recent meta-analysis comparing 3-D navigation techniques to traditional FH screw placement for cervical, thoracic, and lumbosacral pedicle screws, Verma et al37 set out to determine functional outcome. They found, in their pooled results, no neurological complications related to screw malposition in 719 patients instrumented via CAN, compared to 13/569 cases of neurological deficit in the FH group. These results trended towards favoring the navigation technique, though the results failed to reach statistical significance (P = .07). A possibly
They found that CAN used significantly smaller screws, had a significantly larger screw/pedicle diameter ratio, and resulted in significantly fewer revision procedures, with the majority of revision procedures performed for failure of fixation. They concluded that CAN resulted in an optimization of screw diameter and stronger fixation leading to lower rates of screw pullout and need for revision surgery.

Radiation Exposure: Safety of the Surgeon, Patient, and OR Staff

Spine surgery and intraoperative fluoroscopy are intimately associated. Fluoroscopy has been heavily relied upon, traditionally, for localization and guidance of instrumentation for fusion procedures. The hazardous ionizing radiation exposure that the surgeon, patient, and OR staff are subjected to during spinal procedures has been shown to be exponentially increased over other subspecialties of orthopedic and neurosurgery. When comparing radiation exposure experienced by a spine surgeon to other orthopedic subspecialties, a spine surgeon sees 50 times the lifetime radiation dose compared to that of a hip surgeon. To further this alarming statistic, the increasing popularity of MIS, which relies even more on fluoroscopic imaging for percutaneous instrumentation, subjects all parties involved to even more ionizing radiation that has been linked to the development of cataracts, skin erythema, leukemia, thyroid carcinoma, and other neoplasms.

Rampersaud et al first looked at the radiation exposure a surgeon is subjected to during a traditional open posterior lumbar fusion in 2000. The authors measured ionizing radiation exposure to chest, thyroid, and hands during lumbosacral pedicle screw instrumentation in cadavers. They found that even when total fluoroscopy time was minimized to 2 min per case, the annual threshold for radiation exposure, measured in mrem, was surpassed after just 300 cases. Almost a decade later, Bindal et al sought to determine the radiation exposure to the unprotected MIS surgeon performing a transforaminal lumbar interbody fusion. The authors found that the surgeon surpassed the occupational exposure limit after just 194 cases averaging 1.38 levels per case. Three years later, Mroz et al sought to determine the effect of wearing protective thyroid and chest lead, eyewear, and protective gloves during MIS transforaminal lumbar interbody fusion. Their results demonstrated a significant decrease in harmful radiation exposure when the surgeon wore appropriate protective equipment, allowing for placement of 4854 screws and 6396 screws before surpassing the occupational exposure limits for the eyes and hands, respectively. Similarly, Taher et al echoed these findings in MIS lateral lumbar interbody fusion showing that >2700 cases could be performed before the annual radiation exposure threshold was met by the lead-protected surgeon.

Though appropriate radiation protection, such as lead gowns, thyroid shields, protective gloves, and eyewear, decreases radiation exposure to an acceptable level for the surgeon, CAN technology exists that allows for a complete elimination of this concern. Kim et al first sought to expand upon CAN as a means of reducing radiation exposure to the surgeon. While their navigation techniques were less advanced compared to current platforms, as it necessitated some intraoperative fluoroscopy for registration, they still found that navigation significantly reduced fluoroscopy time by almost 100 s per case (57 vs 147 s). Additionally, they found that because the fluoroscopy time was only for registration of images for stereotactic guidance, which does not necessitate close surgeon proximity to the beam, the radiation exposure to the surgeon was undetectable in the navigation group compared to an average of 12.4 mrem of exposure with fluoroscopic techniques. While radiation exposure to the surgeon may be effectively mitigated with CAN, modern platforms rely on CT-scan registration, which subjects the patient to ionizing radiation. This concern was the basis for a study performed by Kraus et al, seeking to compare patient radiation exposure in posterior lumbar fusion procedures utilizing CAN vs fluoroscopy. Their findings suggest that the radiation saved from negating the need for intraoperative fluoroscopy far surpasses the dose required for registration. In their cohort of 40 patients, they found an average effective dose of 0.4 mGy compared to 5.03 mGy experienced by the patient in CAN vs fluoroscopy-based procedures, respectively. The authors concluded that CAN should be used whenever possible, not only to reduce occupational exposure to the OR team, but also to decrease the patient’s effective dose of radiation exposure.

Robot-Assisted Spinal Surgery

The advances in technology that have led to the refinement of CAN techniques previously discussed offer a safe and efficacious alternative to traditional radiation-intense FH for pedicle screw instrumentation. These platforms are not without flaw; however, accuracy depends on several variables including a direct line of sight from the tracking system camera to the instrumentation tools, relative angles between the camera and registered instruments, camera quality, surgeon skill and expertise in acquiring and registering images, and environmental conditions such as heat, humidity, and light. In an attempt to mitigate some of these shortcomings, miniature robotic systems that attach directly to bony landmarks were conceptualized in the early 2000s. These robotic assistants utilize the same CAN platforms, but lack the drawbacks of surgeon interference with the tracking system cameras and introduce the indefatigability and reproducibility inherent to robotic systems.

One of the pioneers and by far the most studied of these robotic-assisted surgical devices for spine surgery is the Spine-Assist/Renaissance robot (MAZOR Robotics Inc, Orlando, Florida). This device operates under a shared-control model,
with 6° of freedom of motion positioning surgical instruments for spinal procedures (Figure 5). It utilizes 3 different outrigger arms, each accommodating a drill guide sleeve. The robotic software, in sync with a CAN, determines which arm produces the most accurate pathway for pedicle instrumentation based on the chosen implant and relative location of the SpineAssist robot to the predetermined entry point and screw trajectory. The robot may be attached directly to a spinous process in the case of open surgery, or attached to a frame triangulated by percutaneously placed guide lines (1 Kirschner wire at a spinous process and 2 Steinmann pins in the posterior superior iliac spines) for MIS procedures. The first step of the process is to obtain and register CT images of the desired spinal levels with the SpineAssist software to create a virtual spinal map for the robot. However, unlike intraoperative real-time navigation, these images may be obtained preoperatively for preoperative templating. The second step involves the templating of desired screw entry point, trajectory, and screw size. This may be done in the OR or even preoperatively based on the 3-D spinal map constructed by the software and transferred to the intraoperative SpineAssist workstation. Once the virtual template for instrumentation has been created, a short verification procedure is performed intraoperatively, which utilizes tracked Kirschner wires that are inserted into the mounted robot, verifying accuracy of the system. This process assures accuracy to the set specifications, less than 1.5-mm deviation of the actual implant from the preoperative template. The final registration involves obtaining 6 still fluoroscopic images for calibration and intraoperative registration purposes. The SpineAssist software then determines the optimal position of the selected arm for insertion of the drill sleeve and a cannulated drill guide is placed in the arm, which is now aligned along the predetermined implant trajectory. The drill is then used to create a cortical punch at the desired entry point; a guide wire is inserted into the vertebral body so a screw pilot hole may be drilled along the guide wire. The appropriate length and diameter screw is then inserted into the pilot hole after pedicle probing and surgeon confirmation of accuracy.

Cadaver studies first verified the accuracy of this novel robotic-assisted technique, reporting an average deviation of 1 mm or less of actual implant position compared to preoperative template. Soon thereafter, several clinical studies sought to expand upon the translational accuracy and efficacy of the SpineAssist robot (MAZOR Robotics Inc®) in vivo. Roser et al found a 99% accuracy rate of lumbosacral pedicle instrumentation using the SpineAssist robot compared to 98% utilizing fluoroscopy guided, and 92% using navigation techniques. Shizas et al reported a 95% accuracy rate vs 92% for robot-assisted vs fluoroscopic-guided lumbosacral pedicle screw instrumentation, and Kantelhardt et al similarly showed 95% accuracy vs 92% using SpineAssist and conventional fluoroscopy, respectively. Interestingly, the only study to date demonstrating a reduced accuracy of screw placement came from Ringel et al in a randomized controlled trial that demonstrated a significantly reduced accuracy rate of lumbosacral pedicle screw instrumentation with the SpineAssist robot (85%) compared to fluoroscopic-guided screws (93%, P = .019). The authors also reported that 10 of the 146 screws placed with robotic assistance necessitated intraoperative removal and FH reimplantation. The authors utilized a percutaneous means of affixation of the robot to the spine using the hover T method (1 K-wire attached to the spinous process and 2 Steinmann pins in the posterior superior iliac spines), and noted instability in the Kirschner wire leading to malposition of the drill sleeves. They also noted skidding of the drill cannula, which they attributed to skidding of the sleeve lateral to the facet joints. They postulated that these errors might be corrected by use of superior fixation for the hover T K-wire and a more lateral entry point with increased medialization to avoid bony overgrowth and extreme slope of the lateral edge of the facet for sturdy docking of the drill sleeve.

In a new application of an existing surgical robot, the ROSA® robot by Medtech (Medtech S.A., Montpellier, France), originally designed for cranial neurosurgical applications, may provide the answer to the technical flaws encountered by Ringel et al. The ROSA robot is a freestanding robotic assistant with a floor-fixable base and a rigid robotic arm (Figure 6). This may help mitigate concerns of fixation strength to bony anatomy like...
those encountered by Ringel et al. Additionally, the robotic arm moves in concordance with the patient, based on the tracking camera monitoring, real-time, several percutaneously placed tracking pins to the patient’s bony anatomy in reference to tracking spheres affixed to the robot. This technology platform, however, has yet to be validated for use in spinal pedicle instrumentation but early clinical results are promising. In their preliminary study on the novel application of the ROSA robot for spinal surgery, Lonjon et al reported an accuracy rate of 97.3% for pedicle screw instrumentation compared to 92% in the FH group. Though seemingly better suited for percutaneous and MIS procedures due to improved robotic arm fixation, these are the first published data of the ROSA robot for spinal applications and more data are needed to validate its use.

A discussion of surgical robotics would not be complete without mention of the Da Vinci Surgical System (Intuitive Surgical). The Da Vinci robot was FDA approved in 2000 for general laparoscopic procedures and is most commonly used for prostatectomies and hysterectomies, but spinal applications of the technologically advanced system have been proposed. The Da Vinci robot operates under the telesurgical model by which the surgeon operates the robot as an extension of his or her own arm from a remote telesurgical booth (Figure 7). The booth is equipped with 3-D vision screens and portals for the surgeon’s hands to control robotic instruments. Among the benefits of this robotic assistant that have led to its widespread use in the fields of general surgery, urology, and gynecology are high definition, stereoscopic vision with magnification up to 10X, tremor filtering, limitless wrist range of motion, and improved surgeon ergonomics. Additionally, the telesurgical model allows for close oversight from a separate both affording override, making it an ideal form of trainee education.

The Da Vinci Surgical System (Intuitive Surgical) has been utilized for laparoscopic anterior lumbar interbody fusion (ALIF) with promising results. The primary obstacles to ALIF remain the ureters and large vessels (aorta, vena cava, and branches thereof) overlying the anterior spine. The first laparoscopic ALIF was reported in 1991, with hopes of shorter hospital stay, quicker recovery, less postoperative pain, and smaller incisions through the MIS approach. However, results failed to show any advantage over open ALIF in regards to length of stay, blood loss, or complication rates, and additionally, the technical demands, often foreign to spine surgeons, resulted in a steep learning curve with increased operative time. For these reasons, the procedure was largely abandoned by spine surgeons. However, with the improved usability of the Da Vinci robot, the procedure and its hypothesized improved efficacy for mobilizing aforementioned approach-related dangers, the Da Vinci-assisted laparoscopic ALIF has again become relevant in the spine realms. Several small case-series studies have evaluated this application of the Da Vinci robot demonstrating successful dissection of overlying large vessels and no ureter- or vessel-related complications. However promising, the use of the Da Vinci is not FDA approved for actual spinal instrumentation and more exploration is necessary to validate its use.

The State-of-the-Art Image-guided Operating Suite

As CAN platforms continue to evolve, so too must the OR in order to accommodate for new equipment. While all of the CAN systems previously described are mobile, the stereotactic tracking camera, CT scanner, and image registration hub still demand more physical space than a simple fluoroscopy machine. Reflectively, the first key element that surgeons should look for in a state-of-the-art operating suite is size and layout of the room.
The OR table itself is also a consideration. Some navigation systems, such as the AiroMobile (Brainlab®), have a custom OR table that rotates a full 360° in order to best accommodate the scanner, tracking camera, surgical technician, and surgeon. This is an attractive feature as it allows for easy adjustment of patient position after scanning without requiring removal of the scanner in case of the event that the reference point is incidentally moved necessitating an intraoperative rescanning and registration. Other factors that may make an OR suite more well adapted for CAN procedures are fixed high-definition monitors to increase case of view during the procedure. Additionally, as decreased radiation exposure is a key feature of CAN, suites that provide “radiation safe” nooks for OR staff during the scanning and registration phase are desirable.

**Future Directions of Navigation and Robotics in Spinal Surgery**

From the numerous studies investigating the safety and efficacy of CAN in pedicle instrumentation, the utility of this technology seems irrefutable. However, the improvements over conventional means of instrumentation are minimal and the cost, at least up front, is great. This begs the question of the cost-effectiveness of navigated instrumentation. One way to hedge the cost of such platforms is to expand upon their applications. Future studies looking at increased utilities of the technology, such as with tumor resection and osteotomies in deformity surgery, may equip the surgeon with the armamentarium necessary to substantially cut the cost of the equipment. Additionally, in a field that relies so heavily upon MRI, coregistration capabilities or even MRI-based navigation may prove to be the future of intraoperative CAN surgery. This would allow the surgeon to not only instrument based on navigation, but potentially perform disk work, mobilize neural elements, and resect tumors safely through even less invasive corridors.

Advances in registration of images are also a consideration that could improve upon current techniques. Merging of preoperative imaging by way of MRI/CT coregistration with a limited-radiation intraoperative scan for “matching” of images would further reduce harmful radiation exposure. This could be attainable by utilizing fine-cut high-radiation CT obtained preoperatively and combining the high-resolution image with a lower radiation dose scanning image obtained intraoperatively. Additionally, if preoperative MRI could be coregistered using similar techniques, the surgeon would be provided with a complete 3-D map of both the bony and neural elements of the spine while further reducing exposure to all OR staff.

Robotic-assisted spinal surgery, though proven to be safe and efficacious for pedicle screw instrumentation, has an even larger cost burden to overcome prior to widespread adoption. Results of pedicle screw accuracy utilizing these robotic arms are at best equal to those reported for CAN alone and currently add little to the effort to improve safety and effectiveness of spinal surgery. Continued efforts to approach zero-error pedicle instrumentation are necessary to validate the use of such robotics in spine surgery, and telesurgical robotic models such as those used by the Da Vinci Surgical System (Intuitive Surgical) may prove to offer more value to spine surgeons. While its indications are currently limited to exposure-related procedures, the Da Vinci robot and similar robotic systems would be valuable for posterior-based surgery and even potentially extra- and intradural tumor surgery where the improved dexterity, tremor elimination, indefatigability and image magnification may improve upon current surgical technique.

**Disclosures**

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