Navigation and Robotics in Pediatric Spine Surgery

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Abstract: Navigation and robotics in pediatric spine surgery have evolved due to the desire for improved safety and efficiency of pedicle screw placement. Computer-guided navigation for pedicle screw placement is based on instrument registration to three-dimensional imaging of the spine and relies on a surgeon's ability to coordinate hand and instrument movements with a computerized screen representing the patient's anatomy. Navigation has been shown to be associated with higher accuracy for pedicle screw placement than other modern techniques such as freehand or fluoroscopic screw guidance. Robotic-assisted pedicle screw placement with real-time navigation affords the surgeon efficient means of rigid trajectory guidance based on anatomical registration of the patient's anatomy. Navigation, when coupled with robotics, aids the surgeon in confirmatory imaging on the screen in real time. Potential downsides include increased setup time, costs, and intraoperative pitfalls, and are presented here in balance with the benefits.

Key Points:
- Current navigation technology is associated with improved accuracy when placing pedicle screws.
- Robotic systems for pedicle screw placement allow for preoperative planning, robotic arm assisted trajectory guidance, and real time navigation for instrument confirmation.
- Further research is needed to justify routine use of robotic technology for pediatric spine surgery.

Introduction

The advent of widespread pedicle screw use in pediatric spinal deformity has led to improved deformity correction, better patient outcomes, shorter hospital stay, and faster return to function.[1-3] The downside of pedicle screw use is misplacement and resultant patient morbidity, as well as unexpected return to the operating room for revision.[4-7] A recent review of the Morbidity and Mortality data from the Scoliosis Research Society revealed screw malposition continues to be a major cause of early implant revision in pediatric spine deformity.[8] The need for enhanced accuracy and efficiency has led to an increased use of computer-guided navigation as well as robotic-assisted placement of pedicle screws. While these techniques are currently associated with a high learning curve and initial longer operating room times, they remain enticing given the potential for increased accuracy of screw placement and decreased radiation exposure to patients and operating room staff.[9-11] The purpose of this article is to review the current concepts associated with computer-assisted navigation and robotics in pediatric spine surgery.

Indications

Currently, in pediatric spine surgery, the indications for image guidance and robotics are expanding, and their use mainly revolves around pedicle screw placement in open surgery. While navigation has been described for surgery in the adult cervical spine, widespread use in the pediatric cervical spine has not been described. Navigation and the emergence of robotics allow for screw fixation from the thoracic spine down to the pelvis. While many reported case series focus on screw placement in adolescent idiopathic scoliosis, routine use of navigation is possible for a wide spectrum of conditions such as congenital scoliosis, neuromuscular scoliosis, spine trauma, and revision surgery. The benefits of navigation can be realized in the most straightforward cases as well as in cases of complex anatomy where surgical landmarks are distorted or do not exist.

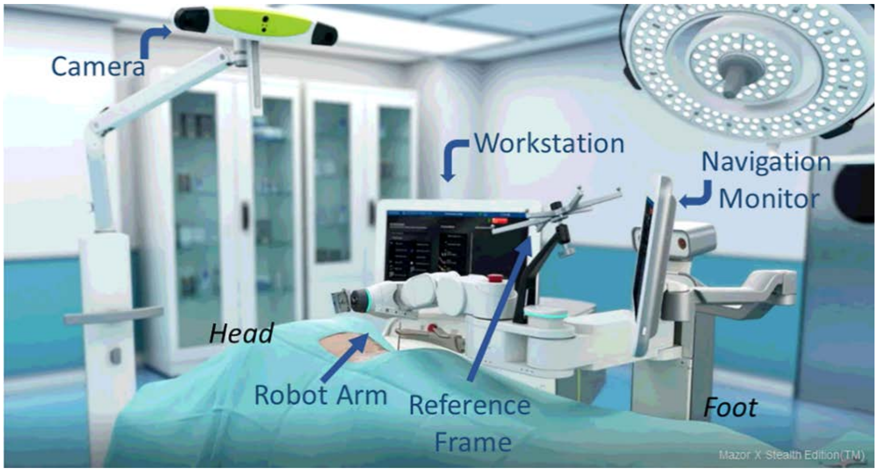

Figure 1. *Basic operating setup for a robotic system with navigation. Schematic modified with permission from Medtronic (Minneapolis, MN).*

Operating Room Requirements

While there currently exists a wide array of navigation options, in general, certain requirements are consistent throughout systems. A navigation workstation is required, which links the navigation camera and the navigation instruments with the patient's anatomy. This is done by attaching a reference frame to the patient, an optical navigation camera, as well as navigated instruments (awl, drill, tap, screwdriver). These systems are compatible with any standard spine frames used for patient positioning. Navigation systems also have a computerized screen which allows for the viewing of the patient's three-dimensional anatomy in concert with the navigated instruments. Robotic systems currently available are compatible with standard navigation systems with the addition of the robotic workstation. The robotic arm attaches to standard spine operating tables and a navigation reference frame is attached to the robotic arm. Lastly, a computer workstation is used for screw planning and as the navigation screen (Figure 1).

These technological advances require significant capital expense. Additionally, specialized support is essential for the successful deployment of this technology, which is usually provided by the vendor. The addition of three-dimensional intraoperative imaging requires an additional purchase such as an O-arm (Medtronic, Minneapolis, MN), which is beneficial for accurate and efficient system registration as well as for post-implant confirmation as needed. Navigation/robotic systems can be used with a preoperative CT scan linked to intraoperative fluoroscopic views if three-dimensional intraoperative imaging such as an O-arm is not available.

Navigation

Image Registration

Surgical navigation systems register the position of an instrument and provide a real-time projection of the instrument on a radiologic image or reconstruction. Most systems rely on either preoperative CT or intraoperative imaging; however, MRI-based platforms are becoming available in some fields given the benefits of no radiation. When registering with a preoperatively obtained CT, the surgeon identifies known anatomic landmarks which are marked and then synchronized between the CT and intraoperative fluoroscopic images. Alternatively, a reference frame or fiducial is clamped to the patient, intraoperative 3D imaging is obtained, and the computer can register and match the coordinates of the imaging to the anatomy (Figure 2).

Obtaining the image preoperatively has certain advantages, including a decrease in anesthesia during the imaging exam, decreased operative time and infection risk, obviating the need to bring advanced imaging into the operating suite. However, registering the

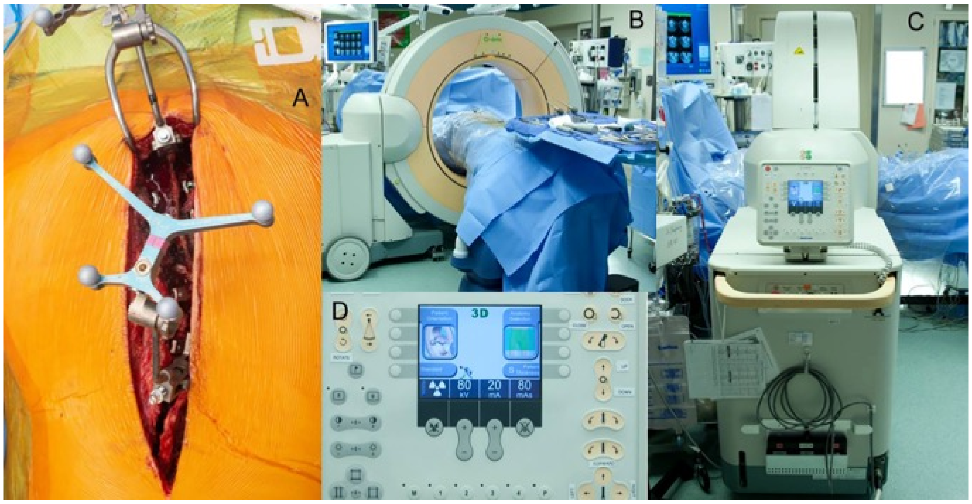

Figure 2. *Workflow for intraoperative CT scan for navigation. A. Since only approximately six to eight levels can be imaged with an intraoperative cone beam CT, two reference frames can be clamped on the spinous processes, and then two scans can be obtained as to only bring in the imaging unit once. B, C. After placement of the reference frames, the patient is wrapped in a sterile translucent sheet to keep the field sterile during the imaging procedure. D. A pediatric low dose setting is achieved by adjusting the settings on the front control panel of the machine. Setting such as 80 kV and 20 mA or lower typically achieves sufficient resolution for navigation, and HD or high-dose settings are never indicated in children.*

preoperative scan with the local anatomy then becomes a critical step and may be challenging for patients with atypical spinal anatomy. Also, any changes in the anatomy either due to intraoperative positioning or surgical dissection will not be displayed when preoperative imaging is used and may affect accuracy.[12] Intraoperative imaging requires a scanner to enter the OR suite, with associated impacts on operative time, infection risk, and additional personnel in the OR. Further, if after the intraoperative scan, the reference frame shifts or the vertebrae move due to facetectomies or change in retractor placement, the projected image of the instrument no longer corresponds with reality. It is essential to continually place the navigated instruments at visually known anatomic landmarks and frequently verify accuracy of the display.[13]

Navigated Screw Placement and Accuracy

In contrast to robotics, all instruments are positioned freely by the surgeon based on navigation imaging, local anatomy, tactile feedback, and visual assessment of local anatomic structures. The navigation reference frame and navigated tools typically do not block or obscure the anatomy from direct visualization. Thus, navigation augments the sensory feedback mechanisms already used by surgeons for freehand screw placement and provides an additional layer of visual information.

Although high rates of accuracy are reported with freehand techniques and postoperative radiographic assessment alone, postoperative CT is likely the most accurate assessment of the screw position.[14] Navigation systems have been shown to improve pedicle screw accuracy as measured on postoperative CT. Return to OR for malpositioned screws is reported in up to 3% of scoliosis cases, which should be considered an avoidable complication.[15-18] Studies report that 5-15% of pedicle screws placed with freehand technique or fluoroscopy are malpositioned. However, not all malpositioned screws are problematic, and the indications for revision are not well established.[4, 19, 20, 21] The region at most risk for screw malposition is in the upper thoracic spine (T3-T8), where the pedicles are small. So if adjunct safety measures are to be used for screw placement, the upper thoracic levels deserve additional attention.[22] CT guided navigation has been shown to improve screw accuracy from 85-90% up to 95-99%.[24-26] Due to the infrequency of neurologic compromise or vascular injuries, it is difficult to detect a reduction in catastrophic screw malposition with the use of navigation. A recent series, however, showed reduced rates of return to OR due to screw malposition after the introduction of CT guided navigation, with no increase in operative time or blood loss.[9] Infection rates, blood loss, and operative times have not been shown to be negatively affected by intraoperative navigation.

Drawbacks of navigation include the expense to obtain and maintain the equipment, as well as personnel to operate the device.

Radiation Exposure with Navigation

For any approach, every effort should be made to reduce radiation exposure, both for the patient and the surgical team. Navigation techniques typically require either a preoperative or an intraoperative CT scan, resulting in increased radiation exposure to the patient. Pediatric spine patients historically have had an increased adulthood cancer risk.[27-30] For this reason, pediatric weight-based settings should be used for every CT scan used in navigation. For intraoperative cone beam CT scan, a variety of protocols have been described in the literature – most commonly reducing the setting to 80 kV, 20 mA, and 80 mAs for patients less than 80 kg.[31-34] One low-dose CT scan at these settings represents approximately 85 thoracic spine fluoroscopy images, an intraoperative PA/lateral 2-view thoracic spine series, or 0.65 mSv.[31] Standard CT dosing, as recommended by industry, results in unacceptably high levels of patient radiation exposure and should be avoided.[35] For reference, annual background radiation is around 3 mSv, and a chest radiographs is 0.1 mSv. Millisieverts measure the effect of radiation on the entire body.[36, 37] Exposure to the surgical team is less with intraoperative navigation than fluoroscopy if the team stands behind an appropriate protective shield for the intraoperative scan.[35]

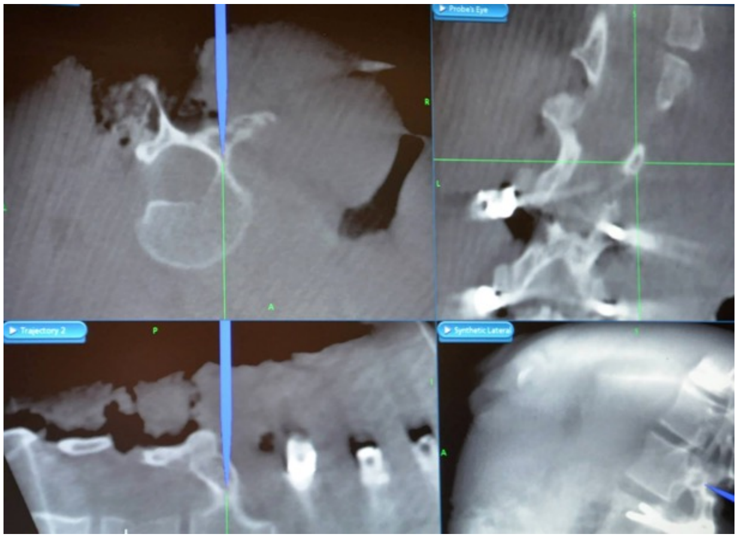

Figure 3. *View of navigated image with optimized trajectory shows 1-mm pedicle diameter.*

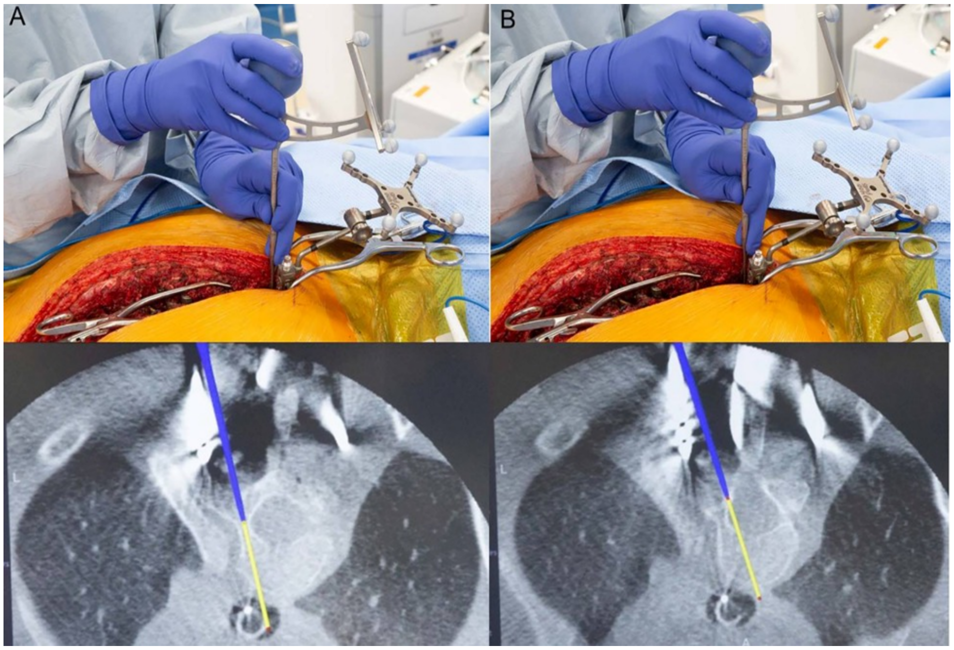

Figure 4. *A) Safe trajectory B) Unsafe trajectory*
Small changes in hand position result in significant differences in trajectory. In the case of instructing a trainee to place pedicle screws, navigation may provide an additional level of safety.

Navigation Benefits

Although the level of radiation is somewhat greater with navigation compared to average use fluoroscopic screw placement, the amount of information provided by navigation is much greater than that obtained from fluoroscopy. Navigation affords the surgeon enhanced insight into the anatomy, small pedicle diameter, and atypical screw trajectories that are employed to optimize screw placement (Figure 3).

Further, navigation technology can be used to determine the optimal screw diameter and length allowable by the patient's anatomy. This can, presumably, improve pull-out strength and overall efficacy. A prime example would be in the upper thoracic spine, where there is little tolerance for error and the need for robust screw fixation (Figure 4). Though all surgeons should remain well versed and comfortable with freehand or fluoroscopic screw placement, navigation provides an additional layer of safety and confidence that is a valuable resource for even experienced spine surgeons.

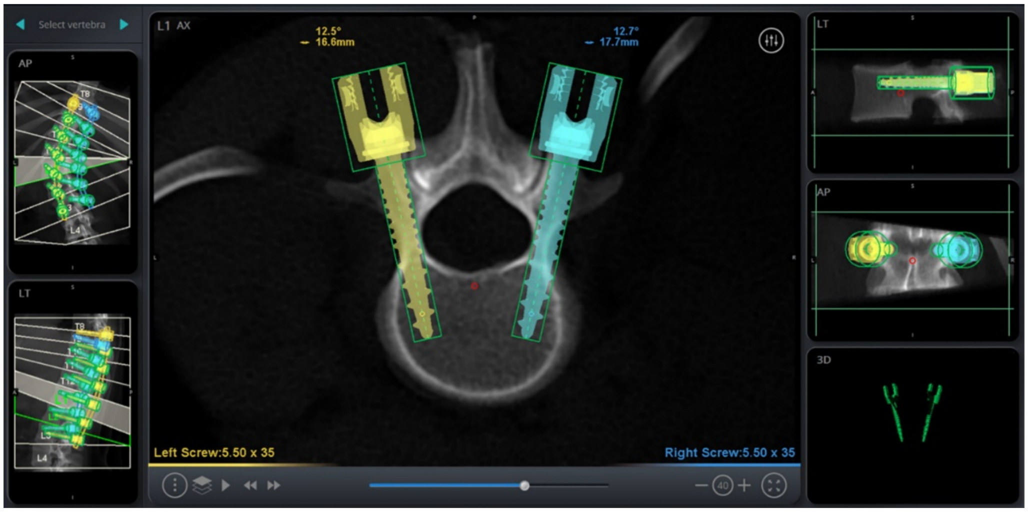

Figure 5. *Image of the workstation screen of the screw planning software. Note the axial, sagittal, and coronal images for screw trajectory, as well as the overall construct planning on the left side of the image.*

Robotics with Intraoperative Navigation

Technical Description

Recent robotic systems have platforms that allow for: preoperative planning of pedicle screw placement, intraoperative trajectory guidance using a robotic arm, and real-time navigation allowing for confirmation of drill and screw pathways. These are shared-controlled robotic systems as both the surgeon and robot control surgical instruments.

The use of preoperative software is beneficial in that it allows planning of pedicle screw size and trajectory by way of either a preoperative CT scan or an intraoperative O-arm scan. The planning software registers the patient anatomy at each vertebral segment and allows for screw planning at each level (Figure 5).

The advantages of this are many: optimization of screw size, determination of screw cascade allowing for ease of rod capture, determination of screw trajectories in difficult pedicle anatomy, and potentially fewer implants open on the field with sterile packaged individual screws.[38] The software programs are included in the main workstation as well as available to be placed on any computer, which allows for preoperative planning.

The successful use of the robotic arm is multifactorial. One of the initial steps is mounting of the arm to the patient's bony anatomy. Currently, two main options exist for bony mounting: clamping of the spinous process in the surgical field with a PEEK clamp(s) or attaching the mount to a Schanz pin which may be placed in the posterior iliac spine or directly into a pedicle. Mounting the robot to the patient is critical for registration and stability of the system (Figure 6 and 7).

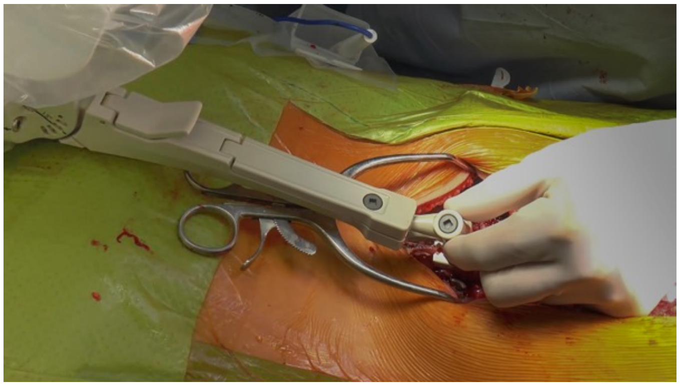

Figure 6. *Intraoperative photo of the robotic bone mount attaching to the PEEK spinous process clamp.*

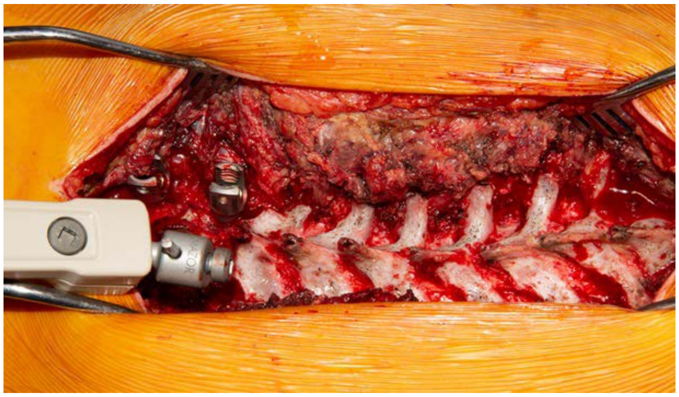

Figure 7. *Intraoperative photo demonstrating the robotic mount attached to a Schanz pin directly placed into the T12 pedicle on the convex side of a right thoracic curve.*

The bone mount must consider the patient anatomy and is done so that the mount does not interfere with the robotic arm trajectory. In general, if you place the mount distally in the construct, then you can adequately register five to eight vertebral segments at and above the attachment, depending on the size of the patient.

Once the robot is mounted, registration of the patient's anatomy is begun for eventual robotic arm guidance. The first step is a three-dimensional volumetric scan of the surgical field. This step is critical as it creates collision avoidance of the arm with the surgical field/patient as the mapping creates a "no-fly zone" for the robotic arm. This prevents inadvertent arm collision with the patient and allows efficient movement of the arm in space (Figure 8, 9).

The next step is synchronizing the robotic reference frame and surgical navigation instruments. The reference frame is attached to the base of the robotic arm, which is at the foot of the table and is in direct line of sight with the fiberoptic navigation camera. Referencing the patient's anatomy at each vertebral segment with the robotic software can be done in one of two ways: synchronization of preoperative CT to intraoperative fluoroscopic imaging; or "Scan and plan" with an intraoperative O-arm.[39] A preoperative CT scan may be obtained and synchronized to intraoperative fluoroscopic images. After the bone mounting has been done, two fluoroscopic views (AP and oblique) are taken using a specialized grid, which allows for the synchronization with the preoperative CT scans. Synchronization is confirmed on the robotic workstation screen to assure that the anatomic landmarks of the CT and fluoroscopic images are perfectly synchronized, thereby confirming that the anatomy seen by the robot perfectly correlates to the preoperative CT scan. The software confirms these by matching multiple reference points on each vertebral body.

Registration of the patient's anatomy may also be done with an intraoperative O-arm scan. After the robotic arm has been mounted and the reference frames set up, an intraoperative O-arm scan may be done, which then registers the vertebral anatomy with the robotic workstation software (Figure 10).

Figure 8. *Intraoperative photo of the robotic arm performing an optical scan of the operative field to aid in collision avoidance and efficiency of arm movement.*

After the scan, then the planning of each pedicle screw may be done, hence the phrase "scan and plan". The advantage of this registration technique is the high reliability as it avoids fluoroscopic registration and diminishes any potential mismatch seen with preoperative CT and surgical prone positioning.[39] Regardless of the registration technique, the number of vertebral segments which can be reliably registered varies from five to eight depending on the size of the

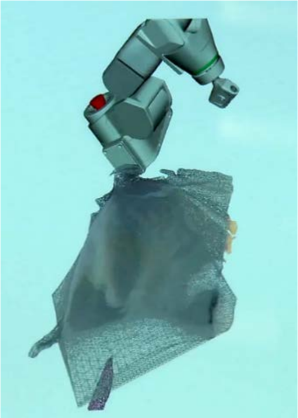

***Figure 9.** Result of topographical scan. Note the area represented is where the robotic arm recognizes as a "no-fly zone" to avoid collision with the operative field.*

patient.[40] For longer constructs, additional registrations are required to capture the anatomy and use the robotic assistance at those levels.

The robotic arm may then be sent to each vertebral segment for screw placement. Placement of the drill guide is performed through the robotic arm. The drill guide's inner sleeve has serrated tines and may be impacted into bone to allow for secure placement (Figure 11).

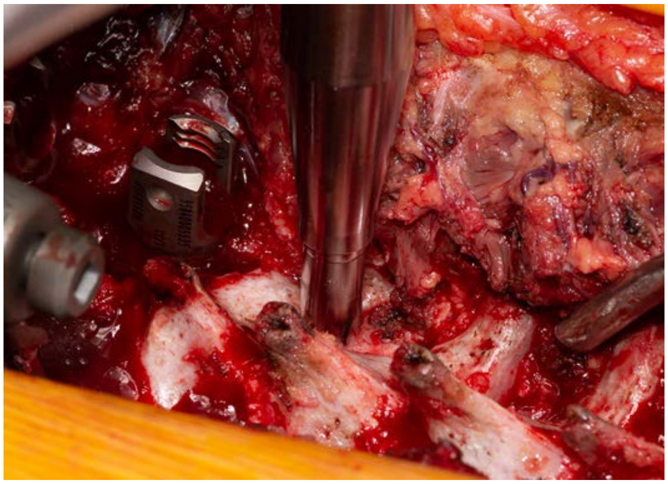

***Figure 11.** Intraoperative photo of drill guide with serrated edges impacted into bone, which provides stability for drilling.*

Once secured to the starting point, the navigated drill is then placed and the pilot hole is created. (Figure 12).

In each step, the navigated instruments are visualized on the screen. After drill removal, navigated tapping can be performed. It is crucial to visualize that the tap enters the drill pilot hole, and then navigated tapping may be done. It is our practice to then probe the hole for a tactile verification, and then place the screw after again confirming that the screw enters the pilot hole. Modern systems allow for placement of the screw via power, and this is done with navigation as well (Figure 13). After screw placement, the robotic arm is sent to the next level with repetition of these steps for each desired screw.

***Figure 10.** Intraoperative photo of a robotic arm with a grid attached and centered over desired vertebral segments for O-arm scanning and registration.*

Confirmation of starting point accuracy may be done by two means. The first being direct visualization, which should confirm an adequate starting point based on the anatomical landmarks the surgeon would recognize for freehand techniques. The second being confirming bony anatomy with the navigation. This can be done by using a passive planar navigation probe and placing it on an anatomical bony landmark, such as the spinous process (Figure 14).

The navigation screen should confirm that the probe position on the landmark corresponds to the probe position seen on the navigation screen. If there is a mismatch, then the surgeon needs to consider re-registration.

Summary

Ultimately, widespread adoption of robotic technology will depend on the ability to show improved accuracy, decreased revision surgery, and manageable operating room costs.[41] Misplaced pedicle screws in pediatric deformity continue to be a mode of implant failure and revision surgery.[5, 8] Aberrant screw placement continues to be a source of concern, given the neurologic and vascular structures at risk during screw placement.[6, 42, 43] Devito published the first series of pediatric patients treated with the SpineAssist first-generation robot and reported an accuracy screw placement rate of 98.3% using postoperative CT scans to grade accuracy and reported no neurologic injuries.[44] Ghasem recently performed a systematic review of the literature for robotic assisted spinal surgery and concluded that they have high levels of accuracy and reproducibility when compared to freehand and fluoroscopic assisted surgery.[45] Li, in a systematic meta-analysis, concluded that robotic-assisted screw placement was more accurate than freehand techniques.[46] The use of intraoperative navigation has been shown to be reliable in improving accuracy and decreasing revision surgery rates in pediatric patients.[9, 26] Currently, no studies are reporting on the accuracy when robotics are combined with intraoperative navigation in the pediatric population.

Figure 12. *Intraoperative photo or drilling through the robotic arm with navigated instruments.*

Radiation exposure in spinal surgery remains a concern for both the patient as well as for the operating room team.[47, 48] In a systematic review and meta-analysis, Gao was able to show less ionizing radiation dosage with robotic-assisted techniques versus freehand techniques.[49] Given the current state of robotic spine surgery with navigation as an intraoperative aid, the radiation exposure likely is equivalent to standard computer aided navigation. The use of pediatric protocols, improved surgeon and radiology technologist training, and experience will clearly diminish exposure to the patient and operating room personnel when compared to initial cases.

From a practical standpoint, robotics offers a significant promise of decreasing the long-term occupational hazards of spine surgery to the surgeon. Radiation exposure malignancy, cervical disc disease, and shoulder degeneration all are potential health problems for practicing spine surgeons.[50] The effects of long-term careers in spine surgery can be deleterious in these areas as well as age-related changes in fine motor skills, making robotic technology promising.[11, 45, 51] The amount of instrument passages in robotic-assisted screw placement is clearly less than in standard techniques such as freehand screw placement. The number of iterations with a handheld awl, recurrent probing, tapping, and screw placement are all significantly reduced. In robotic-guided surgery, there is one drill passage, a tap passage, and screw placement. These steps can be supplemented with probing and be done with power, minimizing both surgeon fatigue and instrument passage.

Pitfalls: Registration remains one of the key elements in robotic spine surgery. Accurate positioning of the robotic arm and hence screw trajectory depends on the software recognizing the anatomical landmarks. As previously mentioned, this can be done with preoperative CT scanning and synchronization to biplanar intraoperative fluoroscopy. There remains some limitations to this, and difficulty with accurate registration has been reported requiring abortion of procedure.[40, 52] The preoperative CT is done supine and prior to any surgical positioning, which may affect accurate registration.[12] Registration with an O-arm has been shown to be accurate and may be done with a reduced dose in pediatric patients, however not all institutions have this imaging modality making standard use not always possible.[32] There are no studies comparing the accuracy in registration between techniques in the pediatric population. Difficulties in registering with fluoroscopy include adequately imaging over the apex of scoliotic curves or in patients with significant kyphosis, which may also be operator dependent (surgeon or radiology tech). The potential advantages of improving registration ability with intraoperative fluoroscopy is the potential future promise of being able to synchronize these images with preoperative MRI scanning rather than CT scanning. Current registration techniques also only allow between five to eight segments to be captured at a time, so in longer constructs, this requires at least one additional registration, which can be time-consuming and detrimental to workflow. Screw placement farther from the reference frame has also been shown to be less accurate with navigation techniques.[53]

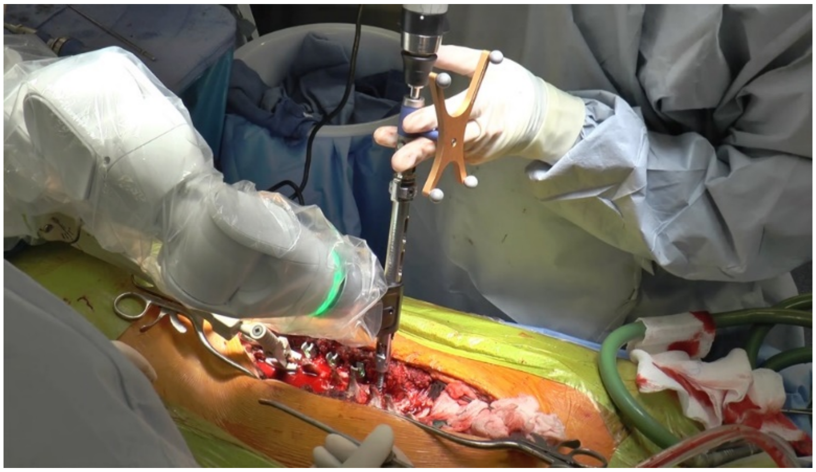

Figure 13. *Photo of pedicle screw placement with power and navigation. Note the power screwdriver through the robotic arm and the navigation spheres pointed at the head of the table toward the navigation camera.*

The stability of spine position greatly affects registration accuracy. Movement of the bone mount, reference frame, or the spine to any significant degree diminishes accuracy. This can be counteracted by ensuring the bone mount is solid and is in a position that won't affect robotic arm placement. Maintenance of spine stability after registration can be challenging in pediatric patients given their inherent ligamentous laxity and small size and is an area that needs to be investigated further.

Skiving refers to instrument slippage, malposition at the level of the bone due to the uneven surface and has been reported to be a pitfall in several studies.[11, 45] This problem can be solved with pilot hole preparation and burring any bony surface away, which blocks a clear pathway of the drill guide to the starting point. The drill guide has serrated surfaces at the end, allowing for stability when brought down to the starting point, which prevents skiving when engaged at the bony surface.

There are currently no studies in the literature regarding the effect of robotic-assisted surgery in pediatric patients on operating room time. Clearly, adult literature has shown an initial increase in time in the operating room when using robotic technology.[45, 49] The increase in surgery time can be difficult to quantify as many of the series included in literature reviews pertain to minimally invasive techniques. As with most new technology, there is a learning curve that must be negotiated in order to obtain a fluid workflow and decrease time in the operating room. It has been our experience that the time increase related to the use of the robot versus freehand techniques is almost all related to registration time. The setup of the robot, draping of the robot, and registration of the navigation tools can all be done by an experienced team member during exposure in order to minimize the effect on the time of surgery. Apart from registration time, screw placement, if anything, is more efficient. Given the advent of surgeon performance pathways, comparison of metrics before and after robotic adoption should be a simple and meaningful undertaking for surgeons.

Finally, the adoption of any innovative technology is associated with a learning curve. The learning curve for robotic surgery has been published with regard to screw accuracy. Schalktlo looked at the learning curve for 13 surgeons placing screws with robotic assistance and found that there was a clear improvement in screw accuracy over time. However, there was a peak of inaccuracies between the time of 10 to 20 cases that was felt to be from surgeons gaining confidence in techniques without quite having mastered the technique.[54] Lieberman reported that with experience, the number of screws placed robotically increased while the number of screws that were aborted and placed freehand decreases.[11] Both of these studies confirm that a high level of awareness by the surgeon with the use of robotic technology is crucial, especially with the initial cases performed.

Embracing Innovative Technology

Innovation is central to the mission of POSNA and its membership. Innovative technologies have consistently enhanced the management of pediatric spine deformity for decades. The introduction of pedicle screw fixation in spine deformity surgery is such an example. In order to maximize their benefit, these technologies must go through a rigorous assessment of efficacy, value, safety, and quality. This scrutiny affords the opportunity for the creation of disruptive technologies designed for optimizing the care we provide for our patients. Safe, accurate, and successful placement of pedicle screws is critical to the surgical management of pediatric spine deformity. Navigation and robotic technologies are designed to provide a consistent, accurate, and highly effective workflow for the placement of pedicle screws.

The capital expense associated with navigation and robotic technologies is quite substantial. The source of funds for the purchase is, in the vast majority of instances, our hospital/institution partners. This creates a situation where we, as surgeons, must decide how aggressively to pursue these resources against the budget of our institutions. These discussions typically revolve around a common theme. What is the expected return on such a large investment? Navigation and robotics have the potential for significant return on investment (ROI). Increasing the accuracy of screw placement, decreasing complications associated with aberrant screw placement, decreasing radiation exposure to patients and OR personnel, and optimization of fixation are examples of ROI that have been reported in adult spine literature. Certainly, these benefits can add to the quality, safety, and value of the care we provide for our patients in the realm of pediatric spine deformity.

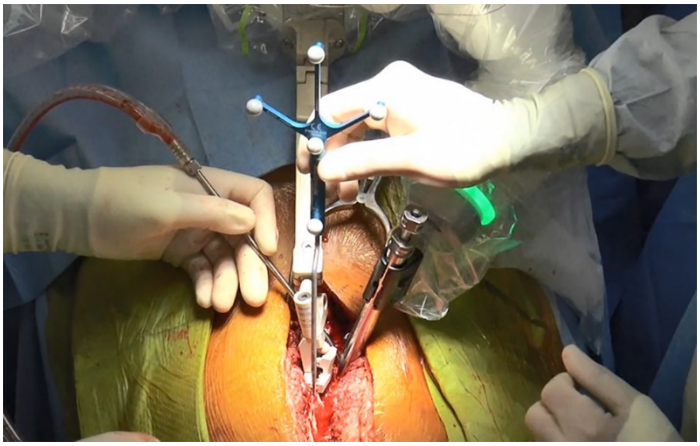

Figure 14. *Confirmation of navigation accuracy may be done by placing a passive planar probe on a known anatomical landmark such as a spinous process and then confirming that this is represented accurately on the navigation screen.*

In general, our outcomes in pediatric spine deformity are good. Thus, large numbers of patients over time are needed to document increased efficacy with the addition of added technologies. The vast majority of pedicle screws placed via freehand technique use fluoroscopic or X-ray assessments to determine the safety and accuracy of screw placement. With navigation and robotics, these assessments are made with a higher level of scrutiny (CT or 3D fluoroscopy). These advances bring forth questions such as, what is an acceptable amount of canal breach when placing pedicle screws? Although we do not yet have answers for such questions, it seems logical to think that more accuracy and precision when placing screws is likely to be better for our patients.

The technologies of navigation and robotics are disruptive and here to stay. Optimizing these applications towards the enhancement of the quality, safety, and value of pediatric spine surgery is a work in progress. At this point, we are rapidly acquiring knowledge and strategies that could prove to be quite beneficial to our field. As we gain further understanding of the limitations, we will continue to develop strategies to mitigate these gaps in the quest to provide the best possible outcomes for our patients.

References

1. Luhmann, S.J., et al., *Correction of moderate (<70 degrees) Lenke 1A and 2A curve patterns: comparison of hybrid and all-pedicle screw systems at 2-year follow-up.* J Pediatr Orthop, 2012. **32**(3): p. 253-8.

2. Bastrom, T.P., et al., *Patient-Reported SRS-24 Outcomes Scores After Surgery for Adolescent Idiopathic Scoliosis Have Improved Since the New Millennium.* Spine Deform, 2019. **7**(6): p. 917-922.

3. Sielatycki, J.A., et al., *The Amount of Relative Curve Correction Is More Important Than Upper Instrumented Vertebra Selection for Ensuring Postoperative Shoulder Balance in Lenke Type 1 and Type 2 Adolescent Idiopathic Scoliosis.* Spine (Phila Pa 1976), 2019. **44**(17): p. E1031-E1037.

4. Baghdadi, Y.M., et al., *Complications of pedicle screws in children 10 years or younger: a case control study.* Spine (Phila Pa 1976), 2013. **38**(7): p. E386-93.

5. Bastrom, T.P., et al., *Major Complications at Two Years After Surgery Impact SRS Scores for Adolescent Idiopathic Scoliosis Patients.* Spine Deform, 2019. **7**(1): p. 93-99.

6. Fujimori, T., et al., *Safety of pedicle screws and spinal instrumentation for pediatric patients: comparative analysis between 0- and 5-year-old, 5- and 10-year-old, and 10- and 15-year-old patients.* Spine (Phila Pa 1976), 2014. **39**(7): p. 541-9.

7. Di Silvestre, M., et al., *Complications of thoracic pedicle screws in scoliosis treatment.* Spine (Phila Pa 1976), 2007. **32**(15): p. 1655-61.

8. Shillingford, J.N., et al., *Instrumentation complication rates following spine surgery: a report from the Scoliosis Research Society (SRS) morbidity and mortality database.* J Spine Surg, 2019. **5**(1): p. 110-115.

9. Baky, F.J., et al., *Intra-operative Computed Tomography-Guided Navigation for Pediatric Spine Patients Reduced Return to Operating Room for Screw Malposition Compared With Freehand/Fluoroscopic Techniques.* Spine Deform, 2019. **7**(4): p. 577-581.

10. Edstrom, E., et al., *Augmented Reality Surgical Navigation in Spine Surgery to Minimize Staff Radiation Exposure.* Spine (Phila Pa 1976), 2020. **45**(1): p. E45-E53.

11. Hu, X. and I.H. Lieberman, *What is the learning curve for robotic-assisted pedicle screw placement in spine surgery?* Clin Orthop Relat Res, 2014. **472**(6): p. 1839-44.

12. Macke, J.J., R. Woo, and L. Varich, *Accuracy of robot-assisted pedicle screw placement for adolescent idiopathic scoliosis in the pediatric population.* J Robot Surg, 2016. **10**(2): p. 145-50.

13. Kochanski, R.B., et al., *Image-Guided Navigation and Robotics in Spine Surgery.* Neurosurgery, 2019. **84**(6): p. 1179-1189.

14. Larson, A.N., et al., *Pediatric pedicle screw placement using intra-operative computed tomography and 3-dimensional image-guided navigation.* Spine (Phila Pa 1976), 2012. **37**(3): p. E188-94.

15. Diab, M., et al., *Neural complications in the surgical treatment of adolescent idiopathic scoliosis.* Spine (Phila Pa 1976), 2007. **32**(24): p. 2759-63.

16. Parker, S.L., et al., *Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws.* Neurosurgery, 2011. **68**(1): p. 170-8; discussion 178.

17. Hicks, J.M., et al., *Complications of pedicle screw fixation in scoliosis surgery: a systematic review.* Spine (Phila Pa 1976), 2010. **35**(11): p. E465-70.

18. Di Silvestre, M., et al., *Complications of thoracic pedicle screws in scoliosis treatment.* Spine, 2007. **32**(15): p. 1655-61.

19. Ughwanogho, E., et al., *Computed tomography-guided navigation of thoracic pedicle screws for adolescent idiopathic scoliosis results in more accurate placement and less screw removal.* Spine, 2012. **37**(8): p. E473-8.

20. Ledonio, C.G., et al., *Pediatric pedicle screws: comparative effectiveness and safety: a systematic literature review from the Scoliosis Research Society and the Pediatric Orthopaedic Society of North America task force.* The Journal of bone and joint surgery. American volume, 2011. **93**(13): p. 1227-34.

21. Floccari, L.V., et al., *Which Malpositioned Pedicle Screws Should Be Revised?* J Pediatr Orthop, 2018. **38**(2): p. 110-115.

22. Heidenreich, M., et al., *At What Levels Are Freehand Pedicle Screws More Frequently Malpositioned in Children?* Spine Deformity, 2015. **3**(4): p. 332.

23. Zindrick, M.R., et al., *Pedicle morphology of the immature thoracolumbar spine.* Spine (Phila Pa 1976), 2000. **25**(21): p. 2726-35.

24. Larson, A.N., et al., *The accuracy of navigation and 3D image-guided placement for the placement of pedicle screws in congenital spine deformity.* Journal of pediatric orthopedics, 2012. **32**(6): p. e23-9.

25. Larson, A.N., et al., *Pediatric pedicle screw placement using intra-operative computed tomography and 3-dimensional image-guided navigation.* Spine, 2012. **37**(3): p. E188-94.

26. Luo, T.D., et al., *Accuracy of Pedicle Screw Placement in Children 10 Years or Younger Using Navigation and Intra-operative CT.* Clin Spine Surg, 2016. **29**(3): p. E135-8.

27. Ronckers, C.M., et al., *Cancer mortality among women frequently exposed to radiographic examinations for spinal disorders.* Radiation research, 2010. **174**(1): p. 83-90.

28. Ronckers, C.M., et al., *Multiple diagnostic X-rays for spine deformities and risk of breast cancer.* Cancer Epidemiol Biomarkers Prev, 2008. **17**(3): p. 605-13.

29. Doody, M.M., et al., *Breast cancer mortality after diagnostic radiography: findings from the U.S. Scoliosis Cohort Study.* Spine (Phila Pa 1976), 2000. **25**(16): p. 2052-63.

30. Simony, A., et al., *Incidence of cancer in adolescent idiopathic scoliosis patients treated 25 years previously.* Eur Spine J, 2016. **25**(10): p. 3366-3370.

31. Su, A.W., et al., *How Does Patient Radiation Exposure Compare With Low-dose O-arm Versus Fluoroscopy for Pedicle Screw Placement in Idiopathic Scoliosis?* J Pediatr Orthop, 2015.

32. Su, A.W., et al., *Switching to a Pediatric Dose O-Arm Protocol in Spine Surgery Significantly Reduced Patient Radiation Exposure.* J Pediatr Orthop, 2016. **36**(6): p. 621-6.

33. Abul-Kasim, K., et al., *Optimization of radiation exposure and image quality of the cone-beam O-arm intra-operative imaging system in spinal surgery.* Journal of spinal disorders & techniques, 2012. **25**(1): p. 52-8.

34. Sarwahi, V., et al., *Low-Dose Radiation 3D Intra-operative Imaging: How Low Can We Go? An O-Arm, CT Scan, Cadaveric Study.* Spine (Phila Pa 1976), 2017. **42**(22): p. E1311-E1317.

35. Mendelsohn, D., et al., *Patient and surgeon radiation exposure during spinal instrumentation using intra-operative computed tomography-based navigation.* Spine J, 2016. **16**(3): p. 343-54.

36. *The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103.* Ann ICRP, 2007. **37**(2-4): p. 1-332.

37. Mettler, F.A., Jr., et al., *Medical radiation exposure in the U.S. in 2006: preliminary results.* Health Phys, 2008. **95**(5): p. 502-7.

38. Agarwal, A., et al., *Implant Prophylaxis: The Next Best Practice Toward Asepsis in Spine Surgery.* Global Spine J, 2018. **8**(7): p. 761-765.

39. Zhang, W., et al., *Accuracy of pedicle screw insertion in posterior scoliosis surgery: a comparison between intra-operative navigation and preoperative navigation techniques.* Eur Spine J, 2017. **26**(6): p. 1756-1764.

40. Takahashi, J., et al., *Accuracy of multilevel registration in image-guided pedicle screw insertion for adolescent idiopathic scoliosis.* Spine (Phila Pa 1976), 2010. **35**(3): p. 347-52.

41. Sethi, R.K., et al., *Improving Complex Pediatric and Adult Spine Care While Embracing the Value Equation.* Spine Deform, 2019. **7**(2): p. 228-235.

42. Sarwahi, V., et al., *Pedicle screws adjacent to the great vessels or viscera: a study of 2132 pedicle screws in pediatric spine deformity.* J Spinal Disord Tech, 2014. **27**(2): p. 64-9.

43. Chan, C.Y.W. and M.K. Kwan, *Zonal differences in risk and pattern of pedicle screw perforations in adolescent idiopathic scoliosis (AIS): a computerized tomography (CT) review of 1986 screws.* Eur Spine J, 2018. **27**(2): p. 340-349.

44. Devito, D.P., et al., *Clinical acceptance and accuracy assessment of spinal implants guided with SpineAssist surgical robot: retrospective study.* Spine (Phila Pa 1976), 2010. **35**(24): p. 2109-15.

45. Ghasem, A., et al., *The Arrival of Robotics in Spine Surgery: A Review of the Literature.* Spine (Phila Pa 1976), 2018. **43**(23): p. 1670-1677.

46. Li, H.M., R.J. Zhang, and C.L. Shen, *Accuracy of Pedicle Screw Placement and Clinical Outcomes of Robot-assisted Technique Versus Conventional Freehand Technique in Spine Surgery From Nine Randomized Controlled Trials: A Meta-analysis.* Spine (Phila Pa 1976), 2020. **45**(2): p. E111-E119.

47. Larson, A.N., B.A. Schueler, and J. Dubousset, *Radiation in Spine Deformity: State-of-the-Art Reviews.* Spine Deform, 2019. **7**(3): p. 386-394.

48. Yoshihara, H. and C.B. Paulino, *Radiation Exposure to the Surgeons and Patients in Fluoroscopic-Guided Segmental Pedicle Screw Placement for Pediatric Scoliosis.* Spine (Phila Pa 1976), 2018. **43**(23): p. E1398-E1402.

49. Gao, S., Z. Lv, and H. Fang, *Robot-assisted and conventional freehand pedicle screw placement: a systematic review and meta-analysis of randomized controlled trials.* Eur Spine J, 2018. **27**(4): p. 921-930.

50. Auerbach, J.D., et al., *Musculoskeletal disorders among spine surgeons: results of a survey of the Scoliosis Research Society membership.* Spine (Phila Pa 1976), 2011. **36**(26): p. E1715-21.

51. Ha, Y., *Robot-Assisted Spine Surgery: A Solution for Aging Spine Surgeons.* Neurospine, 2018. **15**(3): p. 187-188.

52. Hu, X., D.D. Ohnmeiss, and I.H. Lieberman, *Robotic-assisted pedicle screw placement: lessons learned from the first 102 patients.* Eur Spine J, 2013. **22**(3): p. 661-6.

53. Oba, H., et al., *Pedicle Perforation While Inserting Screws Using O-arm Navigation During Surgery for Adolescent Idiopathic Scoliosis: Risk Factors and Effect of Insertion Order.* Spine (Phila Pa 1976), 2018. **43**(24): p. E1463-E1468.

54. Schatlo, B., et al., *Unskilled unawareness and the learning curve in robotic spine surgery.* Acta Neurochir (Wien), 2015. **157**(10): p. 1819-23; discussion 1823.