ROBOTICS IN SPINAL SURGERY:
CURRENT LIMITATIONS AND FUTURE DIRECTIONS

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CRITICAL REVIEW

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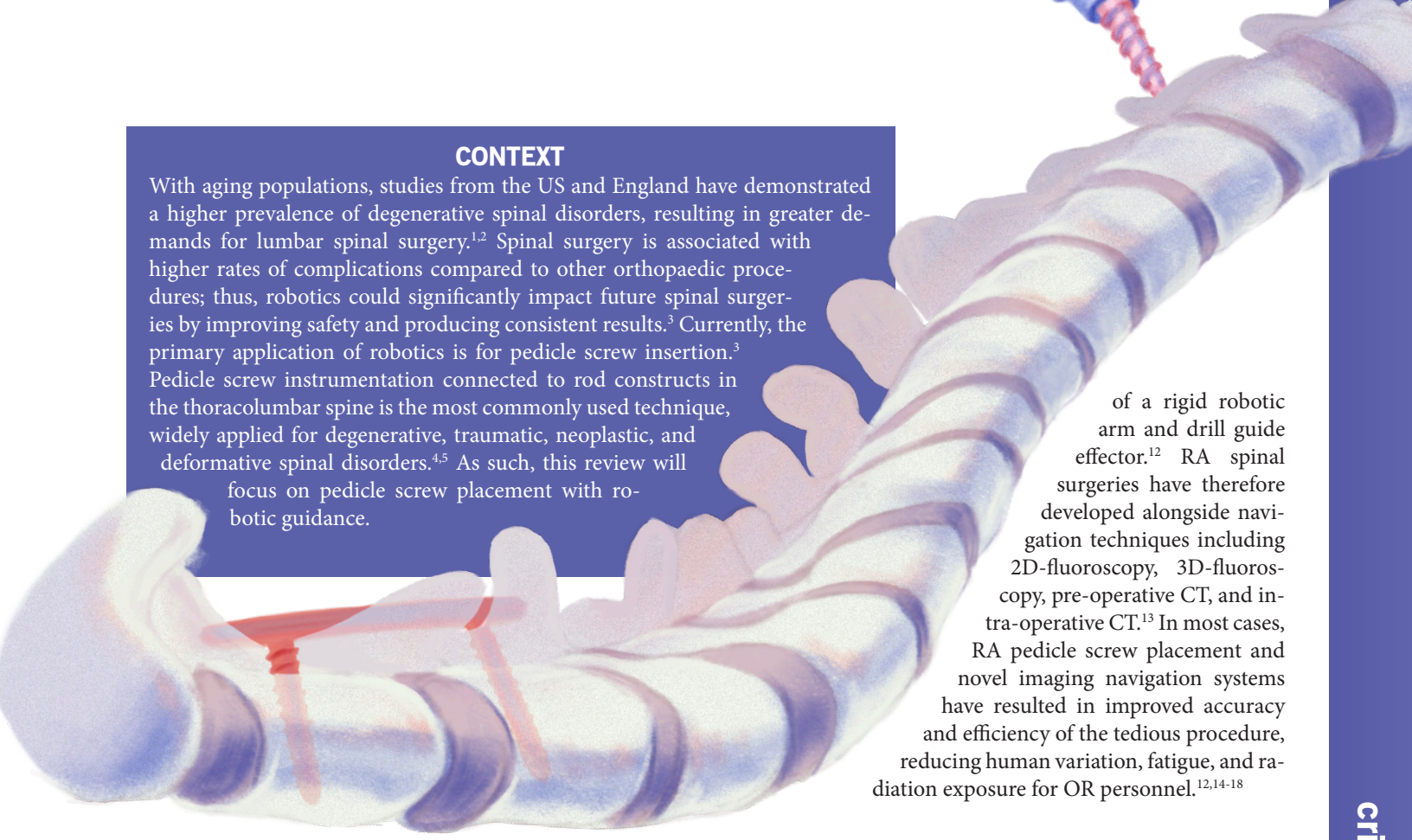
ABSTRACT

Surgical robotics have been introduced in a number of disciplines, with the aim of minimizing tissue disruption, reducing operating personnel radiation exposure, and improving dexterity and efficiency relative to human operation. In spinal surgery, robotic systems are relatively novel, applied to date largely for the placement of pedicle screw instrumentation. Only a few robotic systems have been approved for spinal surgery, and there remain significant barriers to the widespread implementation of surgical robotic techniques. This review provides an overview of robotic systems in spinal surgery and identifies current limitations that must be addressed before clinical use, including clinical merit relative to freehand navigation systems, steep learning curves, and unclear cost-effectiveness.



CONTEXT

With aging populations, studies from the US and England have demonstrated a higher prevalence of degenerative spinal disorders, resulting in greater demands for lumbar spinal surgery.[1,2] Spinal surgery is associated with higher rates of complications compared to other orthopaedic procedures; thus, robotics could significantly impact future spinal surgeries by improving safety and producing consistent results.[3] Currently, the primary application of robotics is for pedicle screw insertion.[3] Pedicle screw instrumentation connected to rod constructs in the thoracolumbar spine is the most commonly used technique, widely applied for degenerative, traumatic, neoplastic, and deformative spinal disorders.[4,5] As such, this review will focus on pedicle screw placement with robotic guidance.

Traditionally, pedicle screw fixation was conducted with the freehand technique.[6] In expert hands, rates of successful placement were as high as 80-90%, though screw malposition can result in severe and potentially permanent clinical sequelae. Malpositioned screws may be associated with long-term poor construct strength and accelerated degeneration of adjacent spinal segments.[7] Over the past two decades, intra-operative 2D-fluoroscopy navigation was introduced into spinal surgery to improve pedicle screw placement accuracy. In these procedures, pre-operative computed tomography (CT) scans were reconstructed to generate a 3D model of the spine.[8] Despite the critical role of fluoroscopy in spinal navigation, operating room (OR) staff and the patient are exposed to significant harmful ionizing radiation.[3,6] Thus, radiation exposure and operating time are important to consider. Modern image-guidance systems using CT scans have significantly reduced radiation exposure to OR staff. Intra-operative CT or 3D-fluoroscopy systems, in particular, allow real-time imaging of the patient in the surgical prone position (as opposed to supine positioning for a pre-operative CT), eliminating errors due to motion between pre- and intra-operative positioning.[9] Intra-operative CT scan-based navigation has resulted in improved pedicle screw placement accuracy compared to 2D-fluoroscopy techniques.[10,11]

Robot-assisted (RA) spinal surgery allows the physician to insert surgical instruments and screws with the use of a rigid robotic arm and drill guide effector.[12] RA spinal surgeries have therefore developed alongside navigation techniques including 2D-fluoroscopy, 3D-fluoroscopy, pre-operative CT, and intra-operative CT.[13] In most cases, RA pedicle screw placement and novel imaging navigation systems have resulted in improved accuracy and efficiency of the tedious procedure, reducing human variation, fatigue, and radiation exposure for OR personnel.[12,14-18]

EVALUATING EFFECTIVENESS

RA pedicle screw insertion has resulted in higher accuracy, safety, and feasibility of the procedure compared with its conventional alternatives. Two meta-analyses demonstrated that RA pedicle screw insertion operations had lower neurological complication rates and reduced risk of pedicle perforation compared to the freehand placement technique.[6] Lieberman et al. also noted RA accuracy rates between 94.5-99%, even in cases involving severe deformity or revision surgeries due to congenital malformations, degenerative disorders, destructive tumors, and trauma.[19] It must be noted, however, that no study to date has demonstrated improved screw placement accuracy with robotic guidance vs. freehand navigation guidance, with most prospective series citing accuracy rates in the 90%+ range for both techniques.[20]

Some current robotic systems include ROSA Spine, the Excelsius GPS, the TiRobot, and the Mazor X.[21] To classify pedicle screw accuracy, the Gertzbein and Robbins system is frequently used, with grades A or B considered clinically acceptable and C or D considered unacceptable, often requiring immediate or delayed revision.[22] The original model of ROSA Spine attained combined accu-

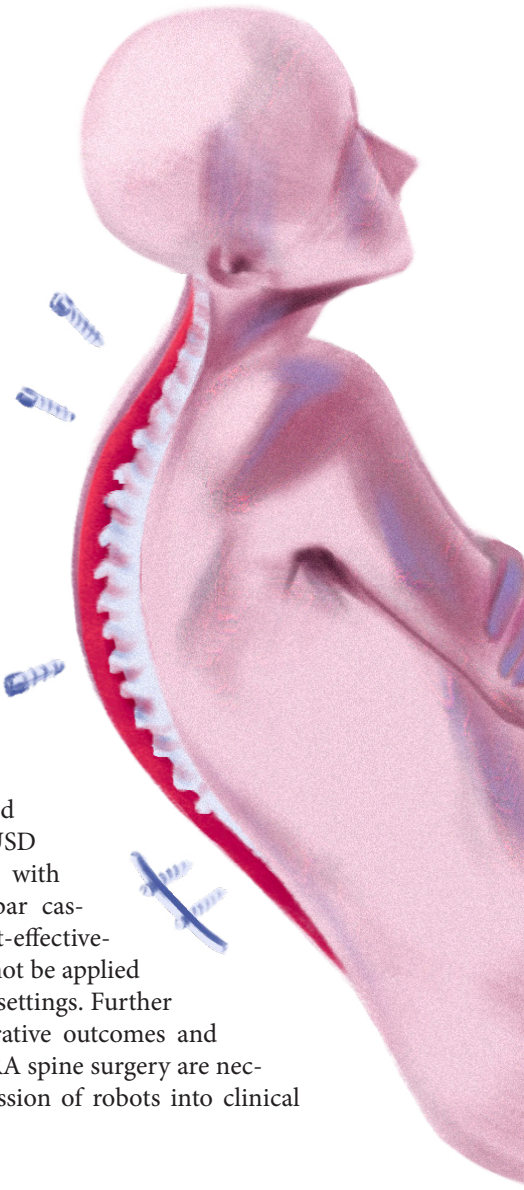
racy rates of 96.3%, 97.3%, and 98.3% with A and B grades.[21] Similarly, the Excelsius GPS attained high levels of accuracy in two retrospective studies. Jain et al. noted 100% of the 66 reviewed post-operative CT screws were categorized as grade A or B, with no major screw-related complications from 643 total screws placed.[23] Elswick et al. reported 97.6% grades A and B for their Excelsius GPS study involving 125 screws.[24] Finally, a randomized prospective trial comparing the TiRobot with free-hand screw placement had similar conclusions, with 95.3% of scores classifying as grade A and 98.7% as combined grades A and B.[14] Evidently, many available robot systems are effective and accurate.

CURRENT PRACTICAL LIMITATIONS

Radiation exposure is one concern that must be addressed in the field of robotic spine surgery. In several studies, the RA technique was reported to provide a 40-70% reduction in intra-operative radiation exposure rates for the patient, the surgeon, and the OR personnel.[19] The RA technique reduced the average radiation exposure time to 34 seconds, compared to the freehand fluoroscopic technique with an average exposure time of 77 seconds.[19] Nevertheless, an average radiation exposure time of 34 seconds is still substantial, and in current use, navigation with intra-operative CT or 3D-fluoroscopy systems is associated with insignificant radiation exposure to OR personnel as they step out of the room during the scans, whereas robotic guidance requires several orthogonal single X-ray shots in the OR for registration.[25,26] Given that pedicle screw insertions are common procedures, the cumulative radiation exposure over one's lifetime can be carcinogenic. Future studies should investigate methods to facilitate the reduction of radiation exposure for subsequent RA systems.

Furthermore, the surgical learning curve could limit widespread clinical application as RA software can be cumbersome and unintuitive.[6] However, there have been several studies indicating that screw placement accuracy improves as more procedures are performed. Schatlo et al. reported that the rate of misplaced screws significantly decreased after surgeons completed 25 RA surgeries, while Hu et al. reported similar findings, where screw placement success rate increased after a surgeon's first 30 patients.[27,28] To address this learning curve, practicing under the supervision of an RA-experienced surgeon and engaging in wet lab or cadaver training prior to surgery in patients is suggested.[3]

The lack of research on clinical outcomes and cost-effectiveness also holds back patient and hospital decisions to undergo RA surgery, specifically due to the novelty of these systems and their questionable benefits relative to freehand navigation.[29] Although evidence suggests intra-operative benefits, little is known about post-operative complications and duration of hospital stay.[29] These factors influence patient perspective and can sway their decision to opt for RA surgery. Furthermore, barriers in assessing cost-effectiveness hinder RA spinal surgeries. One particular study by Menger et al. reported savings of $608 546 USD in a year associated with 557 RA thoracolumbar cases.[30] However, the cost-effectiveness of the robot cannot be applied to smaller healthcare settings. Further reviews on post-operative outcomes and cost-effectiveness of RA spine surgery are necessary for the progression of robots into clinical settings.



FUTURE PROSPECTS

With digital optics continuing to advance in the next decade, high-resolution imaging may serve as an alternative to intra-operative fluoroscopy. 7D Surgical, a Toronto-based company, offers a navigation system that utilizes digital stereoscopic topographical referencing and matches it with pre-operative CT, resulting in rapid image registration and elimination of intra-operative radiation exposure.[21] Augmented reality (AR) is also a visualization technique to explore in spinal surgery, although it must currently remain with freehand actuation. Augmedics Xvision System is an AR platform that provides live 3D navigational feedback, reducing radiation exposure to OR personnel.[21] Similarly, ImmersiveTouch and MagicLeap provide surgeons with intra-operative virtual headsets that allow real-time 3D visualization during the surgery, mitigating differences between the surgical environment and 2D intra-operative imaging.[31] Elmi-Terander et al. achieved an accuracy of 94.1% using an AR surgical navigation system, while Alaraj et al. reported that ImmersiveTouch allowed trainee surgeons

to place screws precisely.[32,33] Although accuracy and radiation exposure are critical to assess, future research should evaluate operative time, clinical outcomes, and intra- and post-operative complications.

CONCLUSION

RA spinal surgery could potentially revolutionize the surgical field. Although clinical implementation is feasible, further research must be conducted to clarify the benefits and drawbacks of robotic spinal surgery. Overall, the evidence demonstrates that RA pedicle screw insertion is more accurate than its freehand counterpart, with several models achieving high GR grades. However, radiation exposure to OR personnel and the learning curve that surgeons face when adapting to new technology remain concerning. Further reviews on cost-effectiveness and clinical outcomes should be conducted to inform hospitals and patients of the benefits, especially as novel high-resolution imaging systems develop alongside RA spinal surgery. Comprehensive reports and evaluations in future publications are essential to pave the way for robotics in the field of spinal surgery.

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Dr. Daipayan (Deep) Guha is a spinal neurosurgeon at Hamilton Health Sciences and an Assistant Professor of neurosurgery at McMaster University. Some of his research interests include emerging imaging technologies for spinal surgery, the applications of augmented reality (AR) in Neurosurgery, and intra-operative three-dimensional spinal navigation.

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