■ INSTRUCTIONAL REVIEW

# Surgeon proficiency in robot-assisted spine surgery

## A NARRATIVE REVIEW

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**Continuous technical improvement in spinal surgical procedures, with the aim of enhancing patient outcomes, can be assisted by the deployment of advanced technologies including navigation, intraoperative CT imaging, and surgical robots. The latest generation of robotic surgical systems allows the simultaneous application of a range of digital features that provide the surgeon with an improved view of the surgical field, often through a narrow portal.**

**There is emerging evidence that procedure-related complications and intraoperative blood loss can be reduced if the new technologies are used by appropriately trained surgeons. Acceptance of the role of surgical robots has increased in recent years among a number of surgical specialities including general surgery, neurosurgery, and orthopaedic surgeons performing major joint arthroplasty. However, ethical challenges have emerged with the rollout of these innovations, such as ensuring surgeon competence in the use of surgical robotics and avoiding financial conflicts of interest. Therefore, it is essential that trainees aspiring to become spinal surgeons as well as established spinal specialists should develop the necessary skills to use robotic technology safely and effectively and understand the ethical framework within which the technology is introduced.**

**Traditional and more recently developed platforms exist to aid skill acquisition and surgical training which are described.**

**The aim of this narrative review is to describe the role of surgical robotics in spinal surgery, describe measures of proficiency, and present the range of training platforms that institutions can use to ensure they employ confident spine surgeons adequately prepared for the era of robotic spinal surgery.**

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## An introduction to robotics in spinal surgery

There are several methods of classifying surgical robots and their application. One system divides surgical robots into two principal categories: surgical computer-aided design/manufacturing (CAD/CAM) systems and surgical assistants.[1]

CAD/CAM systems assist in surgical planning and intraoperative navigation by constructing 3D images from preoperative radiological images.[2] These systems provide the surgeon with an enhanced ability to navigate complex trajectories thereby improving visualization of the surgical anatomy. Surgical assistants are subcategorized as surgical extenders and auxiliary surgical supports.[2] Surgical extenders improve the surgeon's ability to complete certain tasks in a narrow anatomical environment. Auxiliary surgical supports help the surgeon in labour intensive situations, such as holding an endoscope for extended periods.

Surgical robots can be classified further by the level of autonomy incorporated into their design. This describes a spectrum, rather than being a dichotomous classification, and includes passive, semi-active, and active types.[3]

Passive robots do not possess autonomy and are designed to be supportive, while active systems are autonomous and perform a surgical task without the intervention of a surgeon. Robotic autonomy involves more than preprogrammed guidelines and includes complex perception and adaptation to the environment. As a result, autonomous surgical robots are said to have the attribute of 'agency' i.e. purposeful function in the surgical environment.[3]

Surgical robots have several additional defining characteristics, such as the mounting arrangement (The Mount), remote centre of motion (RCM) kinematics and degrees of freedom, and back-driveability.[2]

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The mount refers specifically to the surface to which the robot is attached, either the floor or the ceiling.

RCM kinematics and degrees of freedom describe the number of independent displacements or aspects of motion around a single axis that a robot can perform. These include up/down (pitch), left/right (yaw), rotation (roll), and translation (xy, xz, or yz axes).[4] Although traditionally degrees of freedom would describe a 3D range of movement, robots can perform more than three. Those designed to possess the functionality of a human arm typically have five to seven degrees of freedom.[2]

With the increasing use of minimally invasive procedures, surgical tasks often require the ability to move efficiently in a restricted space. Surgical extenders or robotic assistants are inserted into the working channel (the fulcrum) through a trocar, reducing to four the degrees of freedom in the process; pitch, yaw, roll, and translation along the axis of the trocar.[5] Robots designed with RCM geometry can rotate around a fixed point in the absence of a physical revolute (hinge) joint. This design keeps the two rotational degrees of freedom while allowing the robot to pivot the surgical instrument in relation to the fulcrum, therefore reducing the risk of injury during the procedure. Remote centres can be constrained mechanically or virtually.[5] Mechanical RCM mechanisms include parallelograms, spherical linkages, synchronous belt transmissions, isocentres, and circular tracking arcs.[6] Although mechanical mechanisms are currently preferred to virtual remote centres[7] they are complex, expensive structures that require meticulous calibration and manipulation. Virtual remote centres involve the construction of a programmable remote centre within a controlled algorithm which can create problems with algorithm design and parameters.[6]

Back-driveability is defined as the degree of ease with which a motor or gear motor can be driven by its attached load when power is removed from that motor. It is of particular importance in surgical robotics as a robot could injure a patient if power to the actuator is cut and the robot continues to move. An actuator is the component of a robot responsible for producing any particular degree of freedom. One of the most widely used actuators is the ball-and-screw mechanism which translates rotational motion into linear motion. Other actuators capable of generating linear motion include harmonic drives and cable/belt transmissions.[7] Both need back-driveability to ensure patient safety. The argument for limiting actuator back-driveability is based on restricting the amount of force a tool can exert on a patient's body, and easier manipulation of the robot if there is loss of power. The argument against limiting actuator torque is the risk of potential injury to patients should there be overload of the braking system in the presence of system failure. Currently, both forms exist in the world of robotic surgery.[2]

The first surgical robot used clinically was the PUMA 200 (Westinghouse Electric, Pittsburgh, Pennsylvania, USA). The design objective was the accurate placement of a needle for CT-guided brain biopsy.[8] The versatility, safety, and accuracy (to within 0.05 mm) of the PUMA 200 led to the rapid acceptance of robots in neurosurgical centres and accelerated the expansion of surgical robotics into other surgical specialities. This has particularly been the case in orthopaedics where a combination of advanced imaging technology and robotics has improved the accuracy of arthroplasty.[9,10]

The ROBODOC (Integrated Surgical Systems, Sacramento, California, USA) was designed for human orthopaedic applications in the mid-1980s by Integrated Surgical Systems.[8] Initially it was used for total hip arthroplasty, with the aim of being able to use it in knee arthroplasty, once it had been proved successful.[11,12] The accuracy of the robot was found to be an order of magnitude better than a freehand surgical technique with improved 'fit and fill' of the femoral prosthesis.

Much of spinal surgery relies upon meticulous motor skills to work in a restricted space while minimizing collateral tissue damage particularly to the neural structures. Advances in technology have undoubtedly improved the precision of spinal surgery, in particular pedicle screw instrumentation, which is associated with moderate levels of inaccuracy when used freehand.[13] Robots have only been introduced into spinal surgery relatively recently and the currently available systems (SpineAssist/Renaissance, RosaRobot, ExcelsiusGPS; Mazor, Caesarea, Israel) are primarily used for the insertion of pedicle screws. Regardless of the manufacturer, there are a number of reports of reduced length-of-stay (LOS), reduced radiation, earlier ambulation, and reduced procedure-related complications after robotic-assisted spinal surgery.[1] In addition, preliminary radiological studies have shown an improved accuracy in the placement of pedicle screws according to the Gertzbein and Robbins classification.[14] If these results are reproduced as larger numbers of cases are carried out robotically, the adoption of robotics into spine surgery may, in time, become inevitable.

Early adopters are understandably excited by new surgical technologies that promise significant advantages. However, this has to be tempered by realism, particularly if there are potential conflicts of interest. Both surgeons and hospitals may inadvertently be encouraged to use robotics because of their desire to be identified as an innovator in technological advancement. Conflicts of interest can also potentially arise if there are long-term financial benefits associated with robotic surgery.[14]

Institutions should be mindful of their capacity to afford the large initial cost and subsequent management costs associated with robotic surgical systems. A failure to do so could compromise the internal stability of clinical teams as a result of the misallocation of resources. In addition to the ongoing management costs of the robotic apparatus, hospitals must ensure that surgeons receive adequate training in robotic surgery and provide a budget for that training.

Sachdeva[15] outlined three steps in the acquisition of the skills needed for new technologies. The first is the building of perceptual awareness, understanding the mechanical components of the whole operation, and being able to visualize the process of the procedure needed to achieve the desired outcome. The second step involves guided learning and being able to perform the procedure successfully under supervision, accompanied by feedback. The final step is the autonomous stage and includes the transition to precision and efficiency.

It is likely that competence in the use of robotics will become an essential attribute of both current and aspiring spinal surgeons as the implementation of robotics in spinal surgery gains pace. Traditionally, the acquisition of new surgical skills has been nurtured within clinical training programmes using cadaver workshops and more recently surgical simulators as additional training resources. Cadaver workshops allow trainees to learn in a risk-free environment with a view of the anatomy that is cannot be achieved during live operations.[16] Once trainees have acquired the necessary theoretical knowledge of the new technique, practical skills can be developed and honed under the supervision of their surgical mentors. The success of such programmes is usually defined by the 'take-home' rate – the percentage of surgeons who implement the skills acquired into their daily practice.[17] Such percentages give an insight into the degree of confidence a surgeon in their newly acquired skills and allow training models to be compared.

Defining protocols for standardized surgical training and the assessment of that training involves two methods of evaluating proficiency; first, the learning curve and second, surgical dexterity.[18-20] The learning curve is a commonly used term in surgery to describe the process of gaining knowledge and improving skills to carry out a particular procedure safely and effectively. Typically, the curve describes the number of surgical cases required to show proficiency in a consistent manner.[19] However, the learning curve lacks objective standards of measurement and the endpoint is usually defined by a surgeon's confidence in their own proficiency, which might depend on the clinical environment and the procedure in question. Regardless of endpoint, as surgical proficiency improves an increase in throughput is expected.

Although the learning curve is a popular concept, its ambiguity has led to the development of standardized methods of assessing surgical capabilities, defined as surgical dexterity. For surgical training there are two mechanisms to assess surgical dexterity, Objective Structured Assessment of Surgical Skills (OSATS), and Motion Analysis.[18] OSATS includes eight fields (respect for tissue, time and motion, instrument handling, suture handling, flow of the operation, knowledge of the procedure, overall performance, and quality of the final product), each scored from 1 to 5.[18] A score greater than 24 indicates competence. Motion analysis assesses three parameters (path length, distance travelled, and time taken to complete), which are evaluated using specific software that assesses each parameter digitally. Both the methods can be measured either in a dry lab or by assessing perioperative performance and patient outcome.[18,19] While the latter is generally neither ethical nor practical, and as patient anatomy can vary, making comparisons difficult, the performance of certain standardized tasks in a dry lab (hole threading, knot-tying, suturing) makes comparison between trainees possible.

Surgical simulators provide an additional platform for surgical training, with evidence that they improve a surgeon's performance in the operating room. Torkington et al[20] showed that skills learned in virtual training are transferable to real surgical tasks and comparable to conventional methods of training. A randomized controlled trial by Andreatta et al[21] also showed that skills learned in virtual simulators were applicable clinically. A virtual simulator cohort outperformed the control group in a laparoscopic pig model for: intraoperative time (mean 166 seconds (SD 52) vs mean 220 seconds (SD 39); $p < 0.05$, z-test) and ability to identify objects with the laparoscope (mean 96% (SD 8%) vs mean 82% (15%); $p < 0.05$, z-test) as well as single-handed tasks, and two-handed transfer tasks (intraoperative time; $p < 0.01$, identifying objects; $p < 0.001$, Mann-Whitney U test). Generally, simulators can either be mechanical, where training is conducted in a physical robot stimulator under guidance and supervision, or virtual, where conducted on a computerized platform.[22] As technology improves, virtual simulators are likely to become more popular as they provide efficient statistical feedback on surgical performance, an attribute not offered by their mechanical counterparts.

An efficient protocol for the assessment of robotic surgical simulators is needed to ensure surgeon competency. From a systematic review by Abboudi et al[23] seven parameters were defined that demonstrated simulator efficiency: competence, feasibility, reliability, validity, educational impact, acceptability, and cost-effectiveness. Although Abboudi concluded that simulators provided a safe environment for surgeons to develop their skills, they acknowledged that there was a lack of standardization around the exact metrics used to assess simulators.

Modern methods of acquiring robotic skills such as dual consoles and augmented-virtual-reality (AVR) extend the scope of previous models of surgical training in a safe, reproducible environment. The development of laparoscopic surgery created novel challenges to conventional methods of training, however, requirements such as the exchange of tools and primary surgical control proved difficult to coordinate. As a result, the traditional apprenticeship approach to training was replaced with "conceptualization and reflective observation" in the early stages of skill acquisition.[24] The birth of robotic surgery further complicated matters for trainers. Initially, consoles were designed for single use, distancing mentor and trainee. However, the emergence of dual consoles overcame this problem. The Da Vinci dual surgical system (Intuitive, Sunnyvale, California, USA) allowed surgeons to operate simultaneously which enhanced the process. The system was designed with two collaborative functions; swap mode and nudge mode.[25] Swap mode allows simultaneous operation while also offering instantaneous and effective exchange of all three robotic arms. Nudge mode allows two arms to be controlled (similar to single-surgeon operation), with both surgeons having simultaneous control and experiencing the same movement of instruments. The ability to offer simultaneous operation by two surgeons enhances training and is better than a single surgeon ($p < 0.01$, independent-samples *t*-test) or single trainee ($p < 0.001$, independent-samples *t*-test) approach.[26]

Hanly et al[26] compared the surgical performance of mean time to completion of a complex three-handed Penrose drain task between single-surgeon performance and dual-surgeon performance in consultants and trainees using the DaVinci dual console. Application of 'swap mode', when two surgeons were operating together reduced the intraoperative time taken for complex three-handed tasks when compared to that of a single consultant surgeon ($p < 0.01$, independent-samples *t*-test) and single resident ($p < 0.001$, independent-samples *t*-test). In addition, the study showed the effectiveness of the 'nudge mode' for particular tasks that require precision (e.g. the placement of sutures).

Some virtual fixtures can be integrated into dual consoles to facilitate training. Typically, virtual fixtures exist in two formats;

forbidden-region virtual fixtures (FRVFs) and guidance virtual fixtures (GVFs).[27] FRVFs are a safety feature that stop trainees from entering defined anatomical regions and performing tasks they are not sufficiently experienced to accomplish. In comparison, GVFs provide guidance to the trainee so they can learn particular steps to achieve the best outcome.[27] The dual console has the potential to improve the learning experience of trainees through active participation and to establish itself as a realistic method of training.

Augmented reality in robotic surgery is a recent innovation that offers further opportunities for skill acquisition. The basis of AVR consists of three essential elements: first, a position tracking system that allows continuous adjustment of particular objects and apparatuses in the operative field; second, system control software which constructs images from various inputs of the position tracking system, and third, a head-mounted display device for images.[28] Popular models include ImmersiveTouch (ImmersiveTouch, Chicago, Illinois, USA) and MagicLeap (Magic Leap, Plantation, Florida, USA) which provide surgeons with an intraoperative virtual headset that allows real-time, 3D visualization of a patient's anatomy. AVR is a flexible platform which uses multiple sensory modalities to recreate many of the environmental cues experienced during an actual procedure. Consequently, it eliminates the discrepancy between a surgeon's interpretation of the 3D surgical environment and 2D intraoperative imaging. Some models also allow remote voice control of robotic arms thereby mimicking the position of surgeon arms themselves, producing an efficient surgical system.[28,29]

As a platform for surgeon training, Van Duren et al[29] described the use of AVR to simulate the insertion of a dynamic hip screw for an extracapsular fracture of the hip, showing it replicated the experience of intraoperative insertion of the guide-wire. LeBlanc et al[30] compared the experience of trainee surgeons who used a cadaveric model for skill acquisition with that of an augmented reality simulator. Generic and specific skills scores were similar on both training models in terms of the skills required to perform a colectomy successfully. However, hand-eye coordination and retraction were two generic actions that were better on the cadaver platform. However, the AVR simulator proved to be significantly better at identifying intestinal perforation and difficulties in identifying the left curator ($p = 0.051$, Mann-Whitney U test).

There is evidence that the integration of AVR into spinal surgery is effective. Elmi-Terander et al[31] reported high levels of accuracy when using AVR to assist in the placement of thoracolumbar pedicle screws. No device-related complications were recorded. Kosterhon et al[32] found that AVR provided an accurate and safe method to carry out a complex wedge excision for congenital hemivertebra, while Abe et al[33] noted that AVR provided assistance in establishing the ideal needle trajectory for percutaneous vertebroplasty. Alaraj et al[34] reported their experience of implementing the ImmersiveTouch AVR training model for pedicle screw placement. They showed that the ability to see the pedicle finder with real-time image intensification and monitor the projection on multiple (anteroposterior, transverse, and lateral fluoroscopic) views allowed trainee surgeons to place screws precisely.

AVR models are novel and not yet widely available and it remains to be seen if they will be adopted widely. Nevertheless, it does provide an additional method of developing the surgical skills that will, in all likelihood, be required for the modern era of spine surgery.

In conclusion, robots are likely to be able to help surgeons achieve the best results when used appropriately. There are ethical challenges that should be acknowledged and addressed, particularly regarding the early adoption of what might be seen as unproven technology. One challenge of particular importance is to ensure surgeon competence. Traditional methods of training, such as preceptorships, cadaveric labs, and surgical simulators, have been shown to develop the necessary surgical skills. More modern methods of training such as dual robotic consoles and AVR have yet to be widely adopted but show great promise. In future, as robotic surgery becomes more widely adopted, hospitals and healthcare systems will need to choose their preferred method of training to ensure surgeon proficiency.

**Take home message**

- There has been an adaption of surgical robots across various surgical specialities, including spine surgery.

- Robotic surgery skills will inevitably be a valuable attribute of current and aspiring spinal surgeons.

- This review describes the range of training platforms and measures of proficiency that institutions can use to ensure they employ confident spine surgeons adequately prepared for the era of robotic spinal surgery.

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J. M. McDonnell: Researched understanding robotics and modern methods, Wrote the paper.
D. P. Ahern: Edited the paper.
T. Ó Doinn: Researched ethical challenges of surgical robotics and traditional methods of training.
D. Gibbons: Researchedrobotics in surgery, Wrote the paper.
K. N. Rodrigues: Researched modern methods, Wrote the paper.
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