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Advancing spine surgery: Evaluating the potential for full robotic automation

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ABSTRACT

Introduction: The use of robotic systems in spine surgery is expanding, with growing interest in the potential for full automation. This review explores current robotic technologies, their limitations, and future automation possibilities, focusing on technical and practical aspects.
Research question: What are the current capabilities and limitations of robotic systems in spine surgery, and how might advancements in tracking technologies facilitate a transition toward greater automation?
Material and methods: A narrative review of literature on robotic spine surgery systems was conducted, analyzing benefits, accuracy, limitations, and innovations necessary for full automation. Focus was placed on trajectory-guiding technologies, such as optical tracking and alternative tracking methods.
Results: Current robotic systems (e.g., Cirq®, Mazor X™, ExcelsiusGPS™) assist in trajectory guidance but lack autonomy. Optical tracking systems present challenges, such as obstruction vulnerability and inaccuracies in complex constructs. Conversely, encoder-based tracking demonstrated superior accuracy, offering a promising pathway toward increased automation. The potential advantages of robotics over conventional navigation, including their nature and clinical relevance, remain a topic of active discussion. However, the inherent complexity of spine surgery and the critical role of human decision-making remain substantial barriers.
Discussion and conclusion: While full automation in robotic spine surgery is not yet attainable, advancements in tracking technologies point to a future of enhanced robot-surgeon collaboration, which could optimize clinical outcomes and improve procedural safety.

1. Introduction

In this review, we explore the potential for fully automated spine surgery, where robotic systems could take over either part or the entire procedure, resembling today's stereotactic radiosurgical operations. In such operations, the surgeon's role is largely limited to preoperative planning and intraoperative supervision, while the robotic system executes the procedure (Coste-Manière et al., 2005). Rather than predicting the distant future, our objective is to inform current decision-making regarding innovation paths and resource allocation in spine surgery.

We propose that innovation in this field could follow two main trajectories: (1) the development of tools to enhance surgeons' capabilities and precision, and (2) the creation of systems designed not only to assist but to gradually take over surgical tasks, paving the way toward full automation (Battaglia et al., 2021).

Over the last couple of decades robotics has already significantly integrated in routine life, helping humans to perform independently or under some supervision numerous tasks. Just some of the examples include cleaning, taking care of garden, mowing the lawn, recognising and elimination weeds, preparing food, etc. At industrial level, a visit to a modern car manufacturing plant demonstrates that current robotic technology is capable of automating highly complex tasks. In such

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factories, robots follow blueprints detailing the final product's configuration and materials, executing repetitive tasks with minimal human intervention. Similarly, automation in spine surgery could in theory handle repetitive elements of procedures, while the surgeon remains responsible for oversight and creative problem-solving (planning). For example, robotic laser welding systems used in the construction of aircraft bodies or car frames can perform welds with micro-level precision, ensuring strength and structural integrity while reducing human error, improving production speed, and maintaining consistency across complex geometries (Hongliag et al., 2005).

However, unlike cars, which are uniform in design, every patient presents unique anatomical and clinical particularities and challenges (Amarillo et al., 2021). This introduces significant layers of complexity, as a tailored "blueprint" is required for each procedure. While many aspects of surgery can be standardised, the need for individualised planning underscores the central role of the surgeon.

This narrative review examines the current state, advancements, and future prospects of robotic technologies in spine surgery. Unlike systematic reviews, which are better suited for addressing specific, evidence-based questions with clear quality criteria, a narrative approach allows us to explore broader trends, theories, and innovative ideas. This format is ideal for analysing diverse pathways of innovation and envisioning the future of fully automated surgical systems.

2. A brief overview of robotics in spine surgery

Current commercial robotic technology in spine surgery evolved from conventional image-guided navigation systems (Overley et al., 2017; Jiang et al., 2019). At this stage the robots used in spine surgery do not perform any active steps of surgery, but act as trajectory finders and holders, utilizing optical tracking to establish spatial location in three dimensions (Khalsa et al., 2021). Key to their accuracy are reference markers attached to both the patient and the robot. Infrared cameras are commonly employed to minimise interference from operating room lighting, capturing between 40 and 60 frames per second (Sorriento et al., 2020) either form an active light source or a passive one (reflection). The captured visual data is processed by a computer, which translates it into spatial coordinates. These coordinates are then matched with preoperative surgical plans and converted into robotic commands for execution (Sabri and York, 2021).

The most widely adopted robotic systems in spine surgery today include Cirq®, (Brainlab, Munich), Mazor X™ (Medtronic, Inc., Minneapolis, MN), and ExcelsiusGPS™ (Globus Medical, Inc., Audubon, PA) (MacLean et al., 2024; Khalsa et al., 2021; Farber et al., 2021).

The **Cirq®** is part of a comprehensive modular imaging-guided surgical platform used for both cranial and spine procedures (Gabrovsky et al., 2023; Yamamoto et al., 2024). It is designed to be mounted on the surgical table and offers both passive and active functionality. In passive mode, the surgeon manually adjust the robot to approximate the preplanned trajectory, while the active mode allows the robot to make precise final adjustments to the trajectory autonomously.

The **Mazor X™** is also table-mounted. Unlike Cirq®, Mazor X™ lacks passive trajectory approximation, relying entirely on its active function. This characteristic could be seen as a potential advantage and a step further towards automation as compared to systems that rely partially on passive approximation. It integrates Medtronic's standard navigation system, including an optical camera, and features an additional unspecified camera (Khalsa et al., 2021). To improve the patient-robot interface and to reduce uncoupled movement between the patient and the reference markers, Mazor X™ is anchored to the patient's pelvis, providing enhanced stability during procedures (Buza 3rd et al., 2021, Lee et al., 2021).

Finally, **ExcelsiusGPS™** operates from a separate, independent cart rather than being attached to the surgical table. Like Cirq® and Mazor X™, it functions as both a trajectory finder and holder. Similar to Cirq®, ExcelsiusGPS™ can be used in both cranial and spine surgery. The independent cart design is considered to provide additional stability and other advantages compared to table-mounted systems, however, the spatial patient-robot relation is not fixed by any measures and depends on optical tracking of both (Jiang et al., 2018, Liounakos et al., 2021).

There are no randomised controlled trials to compare the different robots, however, in a meta-analysis that reviewed 46 studies involving 4670 patients and 25,054 screws across four robotic systems, MacLean et al. analyzed the Mazor X™, ROSA® (Medtech, Zimmer-Biomet, Warsaw, Indiana), ExcelsiusGPS™, and Cirq®. The accuracy rates for screw placement (Gertzbein-Robbins classification A or B) were: ExcelsiusGPS (98.0 %), ROSA® (98.0 %), Mazor (98.2 %), and Cirq (94.2 %), with no significant difference between robots. However, it was showed that ExcelsiusGPS™ was more accurate than traditional methods, and both Mazor X™ and ROSA® were more accurate than fluoroscopy (MacLean et al., 2024).

Intraoperative revision rate was lowest for Cirq® (0.55 %) and highest for ExcelsiusGPS (1.08 %), while reoperation rate was lowest for Cirq® (0.28 %) and highest for Mazor X™ (0.76 %). Operative times were similar across robots, but ExcelsiusGPS™ and Mazor X™ showed less blood loss than ROSA®, and Cirq® had the lowest radiation exposure. Overall, robotic systems were more accurate and tended to have fewer reoperations and less blood loss than traditional classic techniques (MacLean et al., 2024).

3. Is there an advantage of robotics compared to conventional navigation?

A central controversy in the adoption of robotic systems for spine surgery revolves around whether they offer sufficient advantages in comparison to non-robotic image guidance to justify their higher costs, particularly since they are essentially robotic arms integrated into conventional navigation systems (Asada et al., 2024; Naik et al., 2022). Critics argue that the accuracy of robotic screw placement, as measured by established scales such as the Gertzbein-Robbins (G-R) scale, shows minimal or no improvement over conventional image-guided methods (Gertzbein and Robbins, 1990). Conventional CT-based optical tracking navigation accuracy, as measured by the G-R scale, is hardly improvable (around 98 %) (Scheufler et al., 2011).

A systematic review of 78 studies published between 1990 and 2018, primarily retrospective, analyzed outcomes for 7858 patients and 51,161 pedicle screws (Perdomo-Pantoja et al., 2019). The authors found that CT-based navigation provided the highest accuracy. However, of the seven robotic studies included, none utilised CT-based registration, and three employed an early robotic device design (miniature robot SpineAssist Mazor), which was later abandoned (Perdomo-Pantoja et al., 2019; Ringel et al., 2012).

Kahn et al. retrospectively compared a series of patients who underwent surgery using either the Mazor X™ robotic system (n = 50) or 3D image-based conventional optical navigation. Both technologies demonstrated high accuracy (99.5 % grade 1 for the robotic group vs 95.1 % in the navigation group), but the robotic group showed additional benefits, including reduced fluoroscopy time (but not radiation exposure), shorter operative times, and decreased hospital stays (Kahn et al., 2019). This findings should be critically assessed on the light of previous studies describing significantly longer duration of robot assisted surgery comparing to free-had techniques (Lonjon et al., 2016).

In another study, Khan et al. 2019 compared robotic guidance and CT-navigation for pedicle screw insertion using cortical bone trajectories for degenerative disc disease. Using the Mazor X™ robotic platform, 92 screws were placed across 24 spinal levels, all achieving Grade I accuracy. In comparison, the CT-navigation group placed 74 screws with similar accuracy, though 5 screws were graded as minor deviations (Grade II). No significant differences were found in operative time, fluoroscopy time, or radiation dose between the two methods (Khan et al., 2020).

Al-Naseem et al. conducted a systematic review and meta-analysis to evaluate robotic-assisted surgery versus navigation-based and freehand techniques for pedicle screw placement in scoliosis surgery. The analysis of 10 observational studies found that robotics significantly improved screw placement accuracy compared to both navigation (OR = 2.02) and freehand technique (OR = 3.06). However, robotics was associated with longer operation times. Other perioperative outcomes, including blood loss, radiation exposure, hospital stay, Cobb angle correction, pain scores, and complication rates, were similar across all three methods (Al-Naseem et al., 2024).

Naik et al. conducted a systematic review and network meta-analysis to compare robotic-assisted pedicle screw placement with conventional methods, including freehand, CT navigation, and 2D/3D fluoroscopy. Analysing 78 studies with over 31,909 screws, they found that robot-assisted and 3D-fluoroscopy techniques achieved the highest placement accuracy, significantly outperforming freehand, CT navigation, and 2D fluoroscopy. The study showed that robot-assisted placement had the lowest rate of misplacement and the highest accuracy ranking (SUCRA score of 0.937). Additionally, robotic assistance was linked to fewer complications, with freehand placement showing the highest complication odds. These findings suggest that robot-assisted pedicle screw insertion offers superior accuracy and safety compared to other methods, despite potential limitations such as generalising categories across studies (Naik et al., 2022).

After reviewing the previously cited studies, it becomes evident that relying on the G-R scale—a proxy for accuracy developed over three decades ago—may inherently constrain the capacity to fully realise the potential benefits of robotic systems. Establishing higher standards is now imperative (Fig. 1.), (Gertzbein and Robbins, 1990; Yamamoto et al., 2024; Jiang et al., 2018; Gubian et al., 2022). When precision is evaluated based, not on the position of the implant in the pedicle, but on how closely the surgical outcomes align with the preoperative plan (i.e. screw trajectory), some studies showed that robotic systems demonstrate a significant advantage over traditional navigation techniques (Farber et al., 2021). Gubian et al. evaluated 140 pedicle screws placed using 3D navigation and found that all screws were rated either A (80 %) or B (20 %) based on the G-R classification. However, 20 % of the screws showed a significant deviation from the intended trajectory, the mean axis deviation was $6.3^\circ \pm 3.6^\circ$, with mean deviations of 5.2 ± 2.4 mm at the screw head and 5.5 ± 2.7 mm at the tip—both significantly exceeding the mean navigation registration error of 0.87 ± 0.22 mm (Gubian et al., 2022).

Is this increased precision clinically important? Hypothetically yes. The increased precision attributed to robotic systems may prove clinically relevant, particularly in complex cases such as long spinal constructs where multiple factors—including screw entry points, trajectory, size, skin incisions, rod bending, and overall alignment—must be meticulously coordinated for and optimal biomechanics construct. In these scenarios, the enhanced accuracy provided by robotic systems could translate into improved clinical outcomes and efficiency, reducing mechanical complications and revision surgeries. If we assume as a fact that robotics increases both precision and efficiency, then the adoption of this innovation can be justified (Farber et al., 2021). Beyond accuracy, there are other advantages of robotics that are harder to quantify but still important, such as a more relaxed, less physically demanding experience for surgeons and an enhanced, more central role for planning.

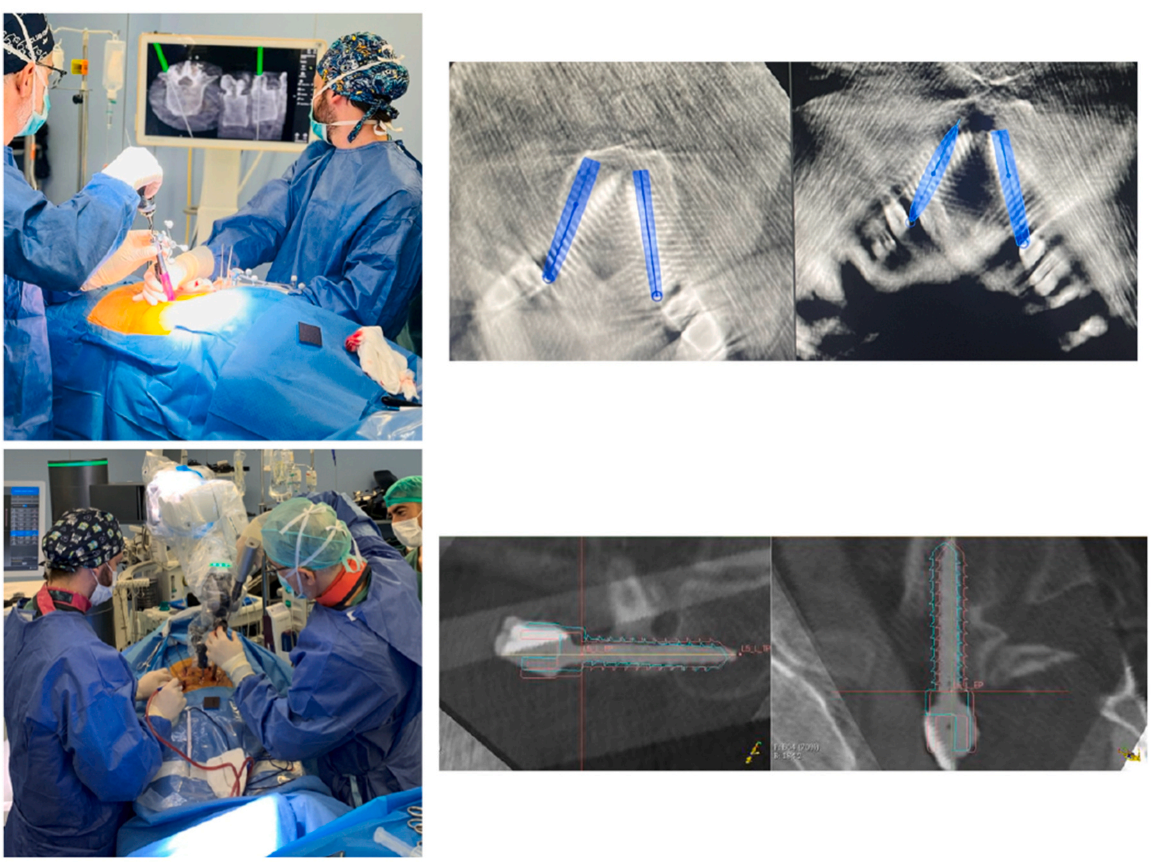

Fig. 1. Comparison of robotic systems versus conventional navigation for pedicular screw placement precision. All screws shown are classified as “A" on the G-R scale, indicating acceptable placement. However, the navigated case demonstrates a significant mismatch between the planned and achieved trajectories, highlighting the potential advantage of robotic systems in achieving greater accuracy. Whether this improved precision translates into meaningful clinical benefits remains a topic of debate.

4. Optical tracking as a limiting factor in automation

The initial conceptualisation of optical tracking systems emerged during World War II with the development of gun directors, optical sighting systems, and infrared technology. The uses of optical tracking nowadays are varied; including virtual reality, augmented reality, intraoperative navigation, and various industrial applications (Sorriento et al., 2020; Marquis, 1966).

The precision of optical tracking systems used for robotic surgery depends on several factors: (1) the distance between the target and the reference markers, (2) obstructions in the camera's field of view, (3) the speed and processing power of the computer, and (4) uncoupled displacement between the spine and the reference markers. (Buza et al., 2021, Geist and Shimada, 2011; Gubian et al., 2022, Liounakos et al., 2021).

Two of those inherent limitations, the distance to the reference (1), and obstructions to the field of view (2) highlight the drawbacks of optical tracking in a confined operating room (Scheufler et al., 2011). A large area around the patient, the "no-flight zone", must remain clear to ensure an unobstructed line of sight for the camera, restricting the surgical team's ability to freely position equipment. This leads to frequent disruptions, as objects like instruments or robotic arms, or even stains on reference markers, can interfere with the system's tracking accuracy.

Although modern computing power has largely mitigated concerns about processing speed and reliability (3), optical systems still face challenges due to the high volume of data generated by high-frame-rate imaging. The system must process tens of images per second to maintain spatial accuracy, making data processing a potential bottleneck (Sorriento et al., 2020). The simpler the algorithms and the smaller the data needed to achieve accurate spatial localisation, the faster and more reliable the computing will be.

Finally, uncoupled displacement (4) between the spine and reference markers remains a significant limitation, particularly when external forces are applied to the spine during surgery. For example, if reference markers are attached to a stable bony structure such as the iliac crest, any movement of the spine relative to this structure—whether due to applied pressure or spinal motion—can result in a loss of precision. Current optical tracking systems lack the capability to account for or register these distortions, which can compromise the accuracy of robotic navigation.

5. Innovations in tracking systems might be the key to progress towards automation

For spine surgery to advance towards full automation, it is essential to overcome the inherent limitations of optical tracking systems. These systems, while accurate, are prone to spatial constraints, obstructions in the field of view, and inaccuracies due to uncoupled movements between the reference markers and the spine (Sorriento et al., 2020; Gubian et al., 2022). As a result, alternative tracking methods are being explored to push the boundaries of automation. These alternative system could potentially be used as a replacement to optical tracking or as a complement in a multimodal tracking approach. Indeed, human surgeons rely on a combination of visual, tactile (haptic), and, to a lesser extent, auditory information as their "tracking" system during procedures.

One particularly promising and remarkably simple solution has been developed to address the limitations of optic tracking (Fig. 2) (Amarillo et al., 2021). Instead of relying on a camera and visual markers, this system utilises a small passive arm with three joints, each equipped with high-precision angle-measuring devices (encoders). Each joint has two axes of rotation, offering six degrees of freedom. The positional data from the joints is transmitted as numerical values to the computer, which then translates it into spatial coordinates. Coupled with preoperative surgical planning, this data can be used to generate precise commands for the robotic system (Geist and Shimada, 2011).

Unlike optical tracking, this passive arm is firmly attached to the spine, allowing it to follow every subtle displacement with remarkable accuracy. Optical systems typically have an error margin of around 1 mm, but this alternative system achieves an average error as low as 0.1 mm—ten times more precise than traditional optical methods (Mascott, 2005; Rudolph et al., 2010; Amarillo et al., 2018, 2021). The lack of cameras makes the overall system more compact, more robust since there is no risk of occlusion, and faster to configure at the beginning of the surgery since the system auto-references the tracking device from a home position.

Other alternative tracking technologies, such as electromagnetic tracking and ultrasound-based localisation, have also shown potential. Electromagnetic systems eliminate the need for a direct line of sight, functioning even with obstructions, while ultrasound-based systems offer continuous tracking of soft tissues and bones. Sensor fusion technologies, which combine data from multiple sources like accelerometers, gyroscopes, and cameras, could offer further enhancements in tracking accuracy and reliability (Sorriento et al., 2020; Geist and

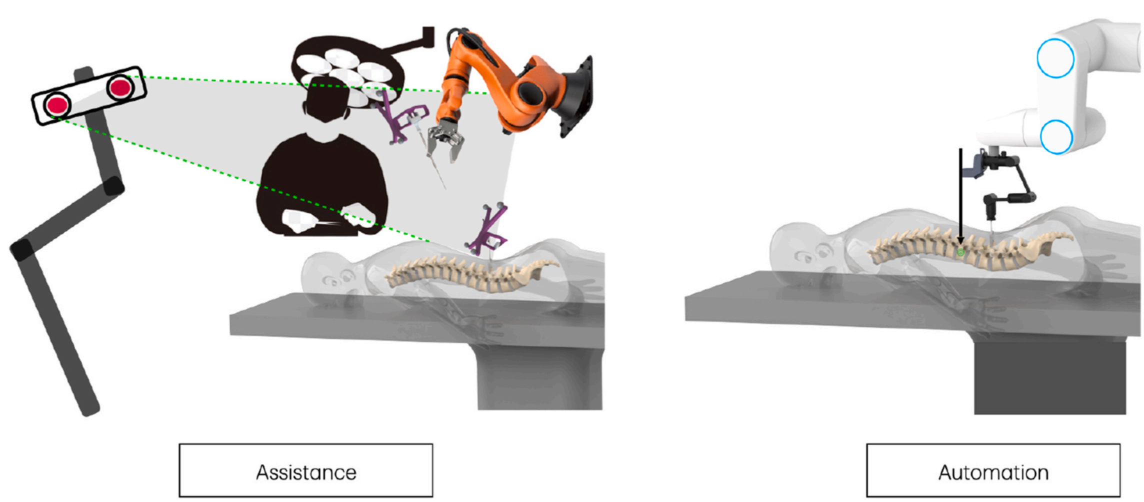

Fig. 2. Schematic representation of image-guided robotic systems utilizing optical tracking (left) compared to mechanical tracking (right). The optical tracking system is designed to enhance the surgeon's capabilities, while the mechanical tracking system is specifically engineered to support the progression toward full automation in surgery.

Shimada, 2011).

The adoption of these alternative systems, particularly the passive arm with high-precision encoders, might hold the key to advancing spine surgery automation. By eliminating the weaknesses of optical systems—such as space constraints and susceptibility to obstructions—these technologies enable greater precision, reduce workflow interruptions, and improve the reliability of robotic surgery. Ultimately, they bring the field closer to fully autonomous surgical procedures.

6. Beyond trajectory finders and holders: automated bone resection

While current robotic systems in spine surgery primarily function as trajectory finders and holders, assisting in the accurate placement of pedicle screws and occasionally serving as retractor holders, they remain largely dependent on the surgeon's control. In these cases, the robot plays a supportive role, with the surgeon maintaining full responsibility for the procedure. However, trajectory guidance is just the first step in the evolution of robotic assistance (Liounakos et al., 2021).

A plausible next phase in robotic spine surgery is the automation of more complex tasks, such as fully automated screw placement and bone resection procedures, including spinal canal decompressions and osteotomies (Khalsa et al., 2021, Liounakos et al., 2021). In a cadaveric study, Wang et al. successfully demonstrated the planning and execution of spinal decompression using a robotic arm with optical tracking and a piezoelectric osteotome system (Wang et al., 2024). Interestingly, The end-effector has 1 degree of freedom vertically and is fitted with a force sensor to complemente the precision offer by the tracking. These tasks represent critical advancements in the progression toward more autonomous surgical systems.

Robot-assisted drilling is already used in total knee arthroplasty. For instance, the Mako (Stryker, Kalamazoo, MI) robotic arm equipped with optical tracking guides the surgeon's drill within the surgical plan's boundaries, precisely matching the implant's shape. This increased accuracy has been linked to shorter hospital stays, better pain management, enhanced knee mobility, and faster recovery (Kayani et al., 2018).

The precision needed to safely perform a robotic laminectomy is arguably greater than 1 mm, significantly surpassing the precision required for knee arthroplasty and that offered by optical tracking alone (Gubian et al., 2022). As previously discussed, the challenge of uncoupled displacement between the reference markers and the target anatomy must be resolved to enable reliable automated screw placement. The same holds true for bone resection, where even greater precision is required due to the critical nature of the structures involved. Current optical tracking systems would struggle with these demands, but the alternative tracking system, which uses a passive arm with high-precision encoders, appears well-positioned to overcome these limitations. Its enhanced accuracy and ability to track every displacement of the spine give it a clear advantage when moving beyond simple trajectory guidance to complex, fully autonomous surgical tasks.

In addition to screw placement, the automation of bone resection tasks such as laminectomies and osteotomies would significantly reduce the surgical burden on the surgeon and increase the reproducibility of these complex procedures. The indications and applications can vary significantly form simple rapid and accurate decompression (such as laminectomies), similar to 3D printer in reverse, to accurate osteotomies for correction of deformities or en-block resection around the primary tumour without violating of its capsule. For this leap to occur, the precision of robotic systems must meet the high standards required to safely and effectively navigate around critical neural and vascular structures. The alternative tracking systems discussed earlier could be key to enabling this next step in automation.

7. The robot and the surgeon

When considering the evolving relationship between the robot and the surgeon in spine surgery, three main possibilities emerge (Lama and Sutherland, 2015):

g. **Co-working Model (Current State):** In this scenario, the surgeon remains fully in charge of the procedure, with the robot serving as a tool. The robot, however, lacks any degree of autonomy and functions purely as an assistant, executing tasks such as trajectory guidance or holding instruments under the direct control of the surgeon (Liounakos et al., 2021).
h. **Tele-manipulation Model:** In this type of systems, the surgeon operates remotely from a console, while the robot reproduces and refines the surgeon's maneuvers at the surgical site. This model is already employed in some robotic-assisted systems, where the robot is capable of improving the precision and stability of the surgeon's movements. Typically, a second human surgeon is present in the operating room to assist with tasks beyond the robot's capabilities (Mehrdad et al., 2021).
i. **Full Automation Model:** In this future possibility, the surgeon's role shifts from performing the procedure to planning and supervising it. The robot takes full control of the surgical execution, carrying out tasks autonomously based on the preoperative plan, with the surgeon overseeing the process to intervene if necessary.

Currently, the co-working model dominates robotic-assisted spine surgery, with incremental improvements in robotic functionality. However, as robotics technology continues to evolve, it is anticipated that the field may shift towards either the tele-manipulation or full automation models. Each model presents unique challenges and opportunities, but the ultimate goal is to enhance surgical precision, reduce human error, and improve patient outcomes through increasingly sophisticated robotic systems.

8. Discussion

The integration of robotics into spine surgery marks a significant technological leap forward. While the current systems primarily assist in trajectory finding and holding, the potential for advanced automation—such as automated bone resection and screw placement—brings new challenges to light. A key aspect of this advancement, centers on addressing a range of technical challenges, liability concerns in cases of surgical complications or adverse outcomes, and the evolving role of the surgeon.

8.1. *The case against automation*

One concern often raised in discussions of automation, particularly in fields like surgery, is the potential impact on surgeons' jobs. This mirrors broader concerns in medicine about the effects of artificial intelligence (AI) on the medical workforce (Hazarika, 2020). The fear is that as robots and AI become more capable, the need for human operators—surgeons in this case—could diminish, threatening their professional roles and livelihoods. This concern is not unique to medicine but arises in any domain where automation is introduced.

Another commonly debated argument is the technical feasibility of creating machines capable of performing such highly complex and variable tasks in a reliable manner. Spine surgery, for instance, requires not only precision and the understanding of the problem situation of the patient, but also adaptability to the unique anatomical variations of each patient, making the automation of such procedures an immense challenge.

Even if the technical hurdles are overcome, the question remains whether automation is desirable. Some argue that fully automated systems could undermine the unique craftsmanship and skill that surgeons bring to their practice. Surgery is not merely a mechanical task but an art, shaped by years of experience, intuition, and decision-making in real time. Just because automation is technically possible does not mean it should be fully realised—there are thus, broader ethical and philosophical considerations about the role of human expertise in healthcare (Battaglia et al., 2021).

8.2. The case for automation

While it is true that automation, wherever implemented, may lead to a short-term decline in job availability, the long-term effects tend to be quite the opposite: more and better jobs. It is an historical fact that automation has often led to the creation of new, higher-quality jobs (World Economic Forum, 2020). For example, modern car factories now employ fewer workers in assembly lines, but the overall number of jobs has increased, with many workers engaged in more specialised, skilled roles. The same potential exists for medicine—automation in surgery could create new opportunities in areas such as robotics management, data analysis, and advanced surgical planning.

The argument that complex tasks, like spine surgery, are beyond the scope of automation is increasingly being disproven. Today, robots are capable of performing tasks that are just as intricate and demanding, if not more so, than those encountered in the operating room. Automation has already shown success in fields like aerospace, where precision, safety, and adaptability are critical, suggesting that even the most complex aspects of surgery can eventually be automated with the right advancements (Hongliag et al., 2005).

As for the desirability of automation, this question can be addressed from a bioethical standpoint. The primary duty of surgeons and the medical field as a whole is to provide patients with the safest, most reliable, and most effective treatment options. No art or way of practicing surgery should be carry out, whenever a better treatment is available for the patient. Surgery is not art for the sake of art, it is for the sake of patients. If automation can enhance surgical precision, reduce errors, and improve patient outcomes, it aligns directly with the core principles of medicine (Han, 2022). In this context, the automation of certain surgical tasks could be seen not only as desirable but as ethically necessary in pursuit of the highest standards of patient care.

8.3. Surgeons and robots: A collaborative future

Rather than envisioning a future where robots replace surgeons, it is more plausible to foresee a collaborative relationship evolving between the two. In this model, the surgeon's role would transition from that of an operator to a supervisor and planner, ensuring that the robot executes tasks in line with the specific needs of each patient. While there may be concerns about the erosion of the surgeon's role in the operating room, automation could ultimately lead to more accurate surgeries, reduced errors, and improved patient outcomes. If this collaboration can be optimised, it may enable surgeons to focus more on complex decision-making, while robots handle the more routine, technically demanding aspects of surgery.

9. Conclusion

As robotic systems continue to evolve, they bring both opportunities and challenges to the field of spine surgery. The development of alternative tracking systems could be pivotal in overcoming current limitations, allowing for greater precision and advancing the possibility of full automation. However, issues of liability, the ethical implications of automation, and the balance between human expertise and robotic efficiency remain central to the discussion. Rather than making surgeons obsolete, the future of spine surgery will likely see an enhanced partnership between human ingenuity and machine precision, ultimately benefiting patient outcomes.

Disclosures

Dr. Samprón reports consulting for Cyber Surgery and Brainlab.

Jorge Presa is the acting CEO of Cyber Surgery.

Dr. Jesús Lafuente reports consulting for Cyber Surgery.

Dr. Härtl reports consulting work for DePuy Synthes, Brainlab, and Aclarion and a financial relationship with RealSpine and OnPoint.

Dr. Marcel Ivanov consulting for Cyber Surgery and Brainlab.

Prof. Dr. Florian Ringel reports consulting and speakers work for Stryker, Brainlab, Spineart, Integra, and Cybersurgery.

The authors collaborated on developing a prototype for an original spinal robot, which led to the creation of the start-up Cybersurgery S.L. This paper stems from that initiative, summarising our conceptual discussions and their foundation in the available evidence to address the technical complexities of this innovation.

Declaration of Generative AI and AI-assisted technologies in the writing process'

During the preparation of this work the authors used ChatGPT in order to improve readability and language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.bas.2025.104232.

References

Al-Naseem, A.O., Al-Muhannadi, A., Ramadhan, M., Alfadhli, A., Marwan, Y., Shafafy, R., Abd-El-Barr, M.M., 2024. Robot-assisted pedicle screw insertion versus navigation-based and freehand techniques for posterior spinal fusion in scoliosis: a systematic review and meta-analysis. Spine Deform 12 (5), 1203–1215. https://doi.org/10.1007/s43390-024-00879-y. Epub 2024 Apr 15. PMID: 38619784; PMCID: PMC11343815.

Amarillo, A., Oñativia, J., Sanchez, E., 2018. RoboTracker: collaborative robotic assistant device with electromechanical patient tracking for spinal surgery. In2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). IEEE, pp. 1312–1317.

Amarillo, A., Sanchez, E., Caceres, J., et al., 2021. Collaborative human–robot interaction interface: development for a spinal surgery robotic assistant. Int. J. Soc. Robotics. 13, 1473–1484. https://doi.org/10.1007/s12369-020-00733-x.

Asada, T., Subramanian, T., Simon, C.Z., Singh, N., Hirase, T., Araghi, K., Lu, A.Z., Mai, E., Kim, Y.E., Tuma, O., Allen, M.R.J., Kim, E., Korsun, M., Zhang, J., Kwas, C., Dowdell, J., Iyer, S., Qureshi, S.A., 2024. Level-specific comparison of 3D navigated and robotic arm-guided screw placement: an accuracy assessment of 1210 pedicle screws in lumbar surgery. Spine J. 24 (10), 1872–1880. https://doi.org/10.1016/j.spinee.2024.05.013. Epub 2024 Jun 5. PMID: 38849051.

Battaglia, E., Boehm, J., Zheng, Y., Jamieson, A.R., Gahan, J., Majewicz Fey, A., 2021. Rethinking autonomous surgery: focusing on enhancement over autonomy. Eur.Urol. Focus 7 (4), 696–705. https://doi.org/10.1016/j.euf.2021.06.009. Epub 2021 Jul 8. PMID: 34246619; PMCID: PMC10394949.

Buza 3rd, J.A., Good, C.R., Lehman, RA Jr, Pollina, J., Chua, R.V., Buchholz, A.L., Gum, J.L., 2021. Robotic-assisted cortical bone trajectory (CBT) screws using the Mazor X Stealth Edition (MXSE) system: workflow and technical tips for safe and efficient use. J. Robot Surg. 15 (1), 13–23. https://doi.org/10.1007/s11701-020-01147-7. Epub 2020 Sep 28. PMID: 32989623.

Coste-Manière, E., Olender, D., Kilby, W., Schulz, R.A., 2005. Robotic whole body stereotactic radiosurgery: clinical advantages of the Cyberknife integrated system. Int. J. Med. Robot 1 (2), 28–39. https://doi.org/10.1002/rcs.39. PMID: 17518376.

Farber, S.H., Pacult, M.A., Godzik, J., Walker, C.T., Turner, J.D., Porter, R.W., Uribe, J.S., 2021. Robotics in spine surgery: a technical overview and review of key concepts. Front Surg. 8, 578674. https://doi.org/10.3389/fsurg.2021.578674. PMID: 33708791; PMCID: PMC7940754.

Gabrovsky, N., Ilkov, P., Laleva, M., 2023. Cirq robotic assistance for thoracolumbar pedicle screw placement: overcoming the disadvantages of minimally invasive spine surgery. Acta Neurochir. Suppl. 135, 389–392. https://doi.org/10.1007/978-3-031-36084-8_59. PMID: 38153498.

Geist, E., Shimada, K., 2011. "Position error reduction in a mechanical tracking linkage for arthroscopic hip surgery,". Int. J. Comput. Assist. Radiol. Surg. 6 (5), 693–698.

Gertzbein, S.D., Robbins, S.E., 1990. Accuracy of pedicular screw placement in vivo. Spine 15 (1), 11–14. https://doi.org/10.1097/00007632-199001000-00004. PMID: 2326693.

Gubian, A., Kausch, L., Neumann, J.O., Kiening, K., Ishak, B., Maier-Hein, K., Unterberg, A., Scherer, M., 2022. CT-navigated spinal instrumentations-three-dimensional evaluation of screw placement accuracy in relation to a screw trajectory plan. Medicina (Kaunas) 58 (9), 1200. https://doi.org/10.3390/medicina58091200. PMID: 36143877; PMCID: PMC9506171.

Hazarika, I., 2020. Artificial intelligence: opportunities and implications for the health workforce. Int. Health 12 (4), 241–245. https://doi.org/10.1093/inthealth/ihaa007. PMID: 32300794; PMCID: PMC7322190.

Jiang, B., Karim, Ahmed A., Zygourakis, C.C., Kalb, S., Zhu, A.M., Godzik, J., Molina, C. A., Blitz, A.M., Bydon, A., Crawford, N., Theodore, N., 2018. Pedicle screw accuracy assessment in ExcelsiusGPS® robotic spine surgery: evaluation of deviation from pre-planned trajectory. Chin Neurosurg J. 4, 23. https://doi.org/10.1186/s41016-018-0131-x. PMID: 32922884; PMCID: PMC7398380.

Jiang, B., Azad, T.D., Cottrill, E., Zygourakis, C.C., Zhu, A.M., Crawford, N., Theodore, N., 2019. New spinal robotic technologies. Front. Med. 13 (6), 723–729. https://doi.org/10.1007/s11684-019-0716-6. Epub 2019 Oct 31. PMID: 31673935.

Kayani, B., Konan, S., Tahmassebi, J., Pietrzak, J.R.T., Haddad, F.S., 2018. Robotic-arm assisted total knee arthroplasty is associated with improved early functional recovery and reduced time to hospital discharge compared with conventional jig-based total knee arthroplasty: a prospective cohort study. Bone Joint Lett. J 100-B (7), 930–937. https://doi.org/10.1302/0301-620X.100B7.BJJ-2017-1449.R1. PMID: 29954217; PMCID: PMC6413767.

Khalsa, S.S.S., Mummaneni, P.V., Chou, D., Park, P., 2021. Present and future spinal robotic and enabling technologies. Oper Neurosurg (Hagerstown) 21 (Suppl. 1), S48–S56. https://doi.org/10.1093/ons/opaa338. PMID: 34128072.

Khan, A., Meyers, J.E., Yavorek, S., O'Connor, T.E., Siasios, I., Mullin, J.P., Pollina, J., 2019. Comparing next-generation robotic technology with 3-dimensional computed tomography navigation technology for the insertion of posterior pedicle screws. World Neurosurg. 123, e474–e481. https://doi.org/10.1016/j.wneu.2018.11.190. Epub 2018 Nov 27. PMID: 30500593.

Khan, A., Rho, K., Mao, J.Z., O'Connor, T.E., Agyei, J.O., Meyers, J.E., Mullin, J.P., Pollina, J., 2020. Comparing cortical bone trajectories for pedicle screw insertion using robotic guidance and three-dimensional computed tomography navigation. World Neurosurg. 141, e625–e632. https://doi.org/10.1016/j.wneu.2020.05.257. Epub 2020 Jun 6. PMID: 32522651.

Lama, S., Sutherland, G., 2015. Robotics for image-guided neurosurgery. In: Golby, A.J. (Ed.), Image-guided Neurosurgery. Elsevier, New York, NY, pp. 475–495.

Lee, N.J., Zuckerman, S.L., Buchanan, I.A., Boddapati, V., Mathew, J., Leung, E., Park, P. J., Pham, M.H., Buchholz, A.L., Khan, A., Pollina, J., Mullin, J.P., Jazini, E., Haines, C., Schuler, T.C., Good, C.R., Lombardi, J.M., Lehman, R.A., 2021. Is there a difference between navigated and non-navigated robot cohorts in robot-assisted spine surgery? A multicenter, propensity-matched analysis of 2,800 screws and 372 patients. Spine J. 21 (9), 1504–1512. https://doi.org/10.1016/j.spinee.2021.05.015. Epub 2021 May 19. PMID: 34022461.

Liounakos, Jason I.MD., Chenin, Louis MD., Theodore, Nicholas MD., Wang, Michael Y. MD., 2021. Robotics in spine surgery and spine surgery training. Operative Neurosurg. 21 (2), 35–40. https://doi.org/10.1093/ons/opaa449.

Lonjon, N., Chan-Seng, E., Costalat, V., Bonnafoux, B., Vassal, M., Boetto, J., 2016. Robot-assisted spine surgery: feasibility study through a prospective case-matched analysis. Eur. Spine J. 25 (3), 947–955. https://doi.org/10.1007/s00586-015-3758-8. Epub 2015 Jan 10. PMID: 25575857.

MacLean, L., Hersh, A.M., Bhimreddy, M., Jiang, K., Davidar, A.D., Weber-Levine, C., Alomari, S., Judy, B.F., Lubelski, D., Theodore, N., 2024. Comparison of accuracy, revision, and perioperative outcomes in robot-assisted spine surgeries: systematic review and meta-analysis. J. Neurosurg. Spine 41 (4), 519–531. https://doi.org/10.3171/2024.4.SPINE23917. PMID: 38968628.

Marquis, D.C., 1966. Optical tracking; a brief survey of the field. Appl. Opt. 5, 481–487.

Mascott, C.R., 2005. Comparison of magnetic tracking and optical tracking by simultaneous use of two independent frameless stereotactic systems. Neurosurgery 57 (4 Suppl. l), 295–301. https://doi.org/10.1227/01.neu.0000176411.55324.1e discussion 295-301PMID: 16234678.

Mehrdad, S., Liu, F., Pham, M.T., Lelevé, A., Atashzar, S.F., 2021. Review of advanced medical telerobots. Appl. Sci. 11, 209. https://doi.org/10.3390/app11010209.

Naik, A., Smith, A.D., Shaffer, A., Krist, D.T., Moawad, C.M., MacInnis, B.R., Teal, K., Hassaneen, W., Arnold, P.M., 2022. Evaluating robotic pedicle screw placement against conventional modalities: a systematic review and network meta-analysis. Neurosurg. Focus 52 (1), E10. https://doi.org/10.3171/2021.10.FOCUS21509. PMID: 34973681.

Overley, S.C., Cho, S.K., Mehta, A.I., Arnold, P.M., 2017. Navigation and robotics in spinal surgery: where are we now? Neurosurgery 80 (3S), S86–S99. https://doi.org/10.1093/neuros/nyw077. PMID: 28350944.

Perdomo-Pantoja, A., Ishida, W., Zygourakis, C., Holmes, C., Iyer, R.R., Cottrill, E., Theodore, N., Witham, T.F., Lo, S.L., 2019. Accuracy of current techniques for placement of pedicle screws in the spine: a comprehensive systematic review and meta-analysis of 51,161 screws. World Neurosurg. 126, 664–678.e3. https://doi.org/10.1016/j.wneu.2019.02.217. Epub 2019 Mar 15. PMID: 30880208.

Ringel, F., Stüer, C., Reinke, A., Preuss, A., Behr, M., Auer, F., Stoffel, M., Meyer, B., 2012. Accuracy of robot-assisted placement of lumbar and sacral pedicle screws: a prospective randomized comparison to conventional freehand screw implantation. Spine 37 (8), E496–E501. https://doi.org/10.1097/BRS.0b013e31824b7767. PMID: 22310097.

Rudolph, T., Ebert, L., Kowal, J., 2010. Comparison of three optical tracking systems in a complex navigation scenario. Comput. Aided Surg. 15 (4–6), 104–109. https://doi.org/10.3109/10929088.2010.530793. PMID: 21070180.

Sabri, S.A., York, P.J., 2021. Preoperative planning for intraoperative navigation guidance. Ann. Transl. Med. 9 (1), 87. https://doi.org/10.21037/atm-20-1369. PMID: 33553380; PMCID: PMC7859791.

Scheufler, K.M., Franke, J., Eckardt, A., Dohmen, H., 2011. Accuracy of image-guided pedicle screw placement using intraoperative computed tomography-based navigation with automated referencing. Part II: thoracolumbar spine. Neurosurgery 69 (6), 1307–1316. https://doi.org/10.1227/NEU.0b013e31822ba190. PMID: 21734616.

Sorriento, A., Porfido, M.B., Mazzoleni, S., Calvosa, G., Tenucci, M., Ciuti, G., Dario, P., 2020. Optical and electromagnetic tracking systems for biomedical applications: a critical review on potentialities and limitations. IEEE Rev. Biomed. Eng. 13, 212–232. https://doi.org/10.1109/RBME.2019.2939091. Epub 2019 Sep 2. PMID: 31484133.

Wang, C., Jiang, S., Li, Z., Zhong, W., Song, X., Liu, H., Hu, L., Li, W., 2024. Accuracy and safety evaluation of a novel artificial intelligence-based robotic system for autonomous spinal posterior decompression. Neurosurg. Focus 57 (6), E16. https://doi.org/10.3171/2024.9.FOCUS24400. PMID: 39616632.

World Economic Forum, 2020. Jobs of tomorrow mapping opportunity in the new economy. https://www3.weforum.org/docs/WEF_Jobs_of_Tomorrow_2020.pdf.

Yamamoto, Y., Fujishiro, T., Hirai, H., Hayama, S., Nakaya, Y., Usami, Y., Neo, M., 2024. Comparison of cervical pedicle screw placement accuracy with robotic guidance system versus image guidance system using propensity score matching. Clin. Spine Surg. 37 (10), E424–E432. https://doi.org/10.1097/BSD.0000000000001616. Epub 2024 Apr 9. PMID: 38637926.