ISSN 1220-8841 (Print)
ISSN 2344-4959 (Online)

Romanian
NEUROSURGERY

Vol. XXXVIII | No. 1 March 2024

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DOI: 10.33962/roneuro-2024-017

Romanian Neurosurgery (2024) XXXVIII (1): pp. 102-108
DOI: 10.33962/roneuro-2024-017
www.journals.lapub.co.uk/index.php/roneurosurgery

The future of spine surgery: technological innovations and advancements. A comprehensive review

Muhammad Jehanzeb

Punjab Institute of Neurosciences, Lahore, PAKISTAN

Keywords
spine surgery,
innovation,
new technology,
robotic surgery,
artificial intelligence,
augment reality,
nano technology,
telemedicine

Corresponding author:
Muhammad Jehanzeb

Punjab Institute of Neurosciences,
Lahore, Pakistan

drjehanzeb28@gmail.com

ISSN online 2344-4959
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First published
March 2024 by
London Academic Publishing
www.lapub.co.uk

ABSTRACT

Spine surgery has witnessed remarkable advancements in technology, techniques, and patient outcomes. The future of spine surgery holds even greater promise as technological innovations continue to shape the field. This comprehensive review explores the role of various technological advancements in the future of spine surgery, focusing on robotic-assisted surgery, augmented reality and virtual reality, 3D printing and custom implants, artificial intelligence and predictive analytics, biomaterials and tissue engineering, nanotechnology, and telemedicine.

Robotic-assisted surgery offers enhanced precision and improved outcomes through real-time guidance and surgical manoeuvre assistance. Augmented reality and virtual reality technologies provide valuable tools for preoperative planning, intra-operative navigation, and surgeon training. 3D printing and custom implants enable personalised treatment approaches with improved fit and alignment. Artificial intelligence and predictive analytics offer decision support, precise diagnostics, and real-time monitoring. Biomaterials and tissue engineering approaches facilitate tissue regeneration and targeted drug delivery. Nanotechnology holds promise for precise diagnostics, real-time monitoring, and targeted therapies. Telemedicine and remote monitoring enhance postoperative care and improve accessibility to specialised care.

These technological advancements have the potential to revolutionise spine surgery by improving surgical outcomes, enhancing patient experiences, increasing accessibility to specialised care, and optimising healthcare delivery. However, challenges such as cost, training, regulatory approvals, privacy, and ethical considerations must be addressed for successful implementation.

Future research directions include further exploration of robotic-assisted surgery, advancement of augmented reality and virtual reality technologies, development of advanced biomaterials and tissue engineering strategies, exploration of nano-materials, and ongoing evaluation of telemedicine and remote monitoring. Collaboration among surgeons, engineers, and scientists is crucial to advancing these technologies and optimising their clinical applications.

In conclusion, the future of spine surgery is shaped by technological advancements that offer improved precision, personalised treatment approaches, and enhanced patient outcomes. While challenges exist, ongoing research and innovation will drive the field forward, improving patient care and advancing the field of spine surgery as a whole.

Introduction

Spine surgery has undergone a remarkable evolution over the years, driven by advancements in technology, surgical techniques, and patient outcomes. The field has witnessed significant improvements in surgical precision, patient safety, and functional outcomes, leading to enhanced quality of life for individuals suffering from various spinal conditions (1). However, the future of spine surgery holds even more promise, as ongoing technological innovations continue to shape the landscape of this specialized field.

The significance of technological advancements in spine surgery cannot be overstated (1). These advancements have the potential to revolutionize surgical techniques, improve patient outcomes, and enhance the overall patient experience. The integration of cutting-edge technologies into spine surgery offers the prospect of greater accuracy, efficiency, and personalized treatment approaches. By exploring the latest innovations and their potential impact, this review aims to provide a comprehensive understanding of the future of spine surgery. (2)

The purpose of this review is to critically analyze the current state of technological advancements in spine surgery and their potential implications. The review will focus on key areas of innovation, including robotic-assisted surgery, augmented reality and virtual reality, 3D printing and custom implants, artificial intelligence and predictive analytics, biomaterials and tissue engineering, nanotechnology, and telemedicine. By examining the existing literature from reputable sources, such as Google Scholar and PubMed, we will evaluate the benefits, challenges, and future prospects associated with these technological advancements in the context of spine surgery.

Robotic-assisted spine surgery

Robotic systems designed for spine surgery have gained significant attention and adoption in recent years. These systems typically consist of robotic arms or platforms, navigation systems, and specialized instruments. Examples of robotic systems used in spine surgery include the Mazor X, Medtronic's StealthStation, and the Globus ExcelsiusGPS (3).

Benefits of robotic assistance, including enhanced precision and improved outcomes

Robotic-assisted spine surgery offers several potential benefits compared to traditional techniques. The use of robotics allows for enhanced precision and accuracy in surgical maneuvers, enabling surgeons to perform complex procedures with increased control (4). Robotic systems provide real-time feedback, which aids in optimal implant placement and alignment. This improved precision can potentially lead to better surgical outcomes, reduced complication rates, and improved patient satisfaction (3,4,5).

Robotic-assisted spine surgery has been utilized in various procedures, including pedicle screw placement, tumor resection, and spinal deformity correction (3). Robotic systems assist surgeons in preoperative planning, intraoperative navigation, and guidance during procedures. The ability to preoperatively plan trajectories and simulate surgeries allows for optimized surgical strategies and implant placement. Future possibilities for robotic-assisted spine surgery include expanding the scope of procedures, incorporating artificial intelligence for automated planning, and integrating robotics with other advanced technologies such as augmented reality (4,5).

Despite the potential benefits, widespread adoption of robotic-assisted spine surgery faces certain challenges. One significant challenge is the cost associated with implementing and maintaining robotic systems. The initial investment and ongoing expenses can limit the accessibility of these technologies in many healthcare settings (3). Surgeon training and learning curve are also important considerations for successful adoption. Training programs are necessary to ensure surgeons become proficient in utilizing the robotic systems effectively (5). Additionally, concerns regarding surgical workflow disruption, potential technical failures, and patient safety require careful consideration (5).

Augmented reality and virtual reality

Augmented reality (AR) and virtual reality (VR) technologies have shown potential in various aspects of spine surgery. AR can overlay digital information onto the surgeon's view, providing real-time guidance, anatomical visualization, and trajectory planning. VR creates immersive virtual environments that enable surgeons to interact with three-dimensional models of the spine for surgical planning and simulation (6).

AR and VR can enhance preoperative planning by allowing surgeons to visualize and interact with patient-specific anatomy in a virtual environment. Surgeons can accurately assess the patient's anatomy, simulate surgical maneuvers, and plan optimal trajectories for instrumentation placement (7). These technologies enable a comprehensive understanding of the patient's pathology, facilitating precise surgical strategies.

AR-based navigation systems can provide real-time guidance during spine surgeries. Surgeons can view patient-specific anatomy overlaid with virtual information, such as preoperative plans, instrument positions, and critical structures, improving accuracy and reducing reliance on fluoroscopy (6,7). The integration of intraoperative imaging with AR technology allows for precise localization and instrument tracking, enhancing surgical precision.

AR and VR technologies offer valuable tools for surgeon training and education. Virtual simulations can replicate complex surgical scenarios, allowing surgeons to practice procedures in a risk-free environment (8). Surgeons-in-training can gain hands-on experience, refine their skills, and develop proficiency before performing surgeries on actual patients. Additionally, these technologies can be utilized for remote surgical mentoring and collaboration, enabling experts to provide guidance and feedback to surgeons in real-time (8).

The use of AR and VR technologies in spine surgery has the potential to improve surgical outcomes and enhance the patient experience. Precise preoperative planning and intraoperative guidance can lead to more accurate instrument placement, reduced complications, and improved surgical outcomes (9). Moreover, the visualization and interactive nature of AR and VR technologies can enhance patient education, enabling patients to better understand their condition and the planned surgical intervention, ultimately leading to increased patient satisfaction.

3D PRINTING AND CUSTOM IMPLANTS

3D printing, also known as additive manufacturing, is a technology that allows the creation of three-dimensional objects from digital designs by layering materials. In the context of spine surgery, 3D printing has gained attention due to its ability to produce patient-specific implants and surgical tools with high precision and accuracy (10). The technology enables the fabrication of complex geometries that are challenging to achieve using traditional manufacturing methods.

One of the significant advantages of 3D printing in spine surgery is the ability to create patient-specific implants tailored to individual anatomies. Based on patient-specific imaging data, such as CT or MRI scans, custom implants can be designed and manufactured to fit the patient's anatomy precisely (11). Additionally, surgical tools, such as patient-specific guides or templates, can be 3D printed to assist surgeons in accurately placing implants or performing precise osteotomies.

Custom implants offer several advantages over standard off-the-shelf implants. The personalized design ensures a precise fit to the patient's anatomy, resulting in improved implant alignment and stability (12). This improved fit can potentially lead to better surgical outcomes, reduced risk of complications, and enhanced long-term implant performance. Furthermore, custom implants can address complex anatomical variations or defects that cannot be adequately addressed with standard implants.

Currently, 3D printing is utilized in spine surgery for various applications, including patient-specific cages for spinal fusion, intervertebral disc replacements, and osteotomy guides (11,12). The technology has the potential to expand to other areas, such as patient-specific pedicle screw guides, anatomical models for surgical planning and education, and bioresorbable implants for spinal fusion. As the technology continues to advance, the possibilities for customized implants in spine surgery are likely to expand further.

While 3D printing offers tremendous potential, there are challenges and regulatory considerations that need to be addressed. The quality control and standardization of 3D-printed implants need careful consideration, ensuring their safety and effectiveness (13). Regulatory agencies, such as the U.S. Food and Drug Administration (FDA), have provided guidelines for the use of 3D-printed medical devices, and adherence to these regulations is crucial. Additionally, cost-effectiveness, scalability, and the integration of 3D printing into existing healthcare systems are factors that need to be considered for widespread adoption.

ARTIFICIAL INTELLIGENCE AND PREDICTIVE ANALYTICS

Artificial intelligence (AI) has the potential to revolutionize spine surgery by enabling the analysis of vast amounts of data and extracting valuable insights. AI algorithms can assist in various aspects, including surgical planning, intraoperative guidance, and postoperative monitoring. By leveraging machine learning and deep learning techniques, AI can process complex data sets and provide valuable decision support to surgeons (14). AI systems can learn from previous surgical cases and continuously improve their performance, enhancing surgical outcomes.

Predictive analytics utilizes AI algorithms to analyze patient-specific data, such as demographics, medical history, and imaging studies, to predict surgical outcomes and assess risks. By integrating patient data with AI models, surgeons can make informed decisions about surgical approaches, anticipated complications, and expected outcomes. Predictive analytics can help optimize surgical planning, improve patient selection, and enhance patient counseling regarding potential risks and benefits (15).

AI algorithms have demonstrated significant potential in image recognition and diagnostic support for spine conditions. By analyzing medical images, such as X-rays, CT scans, and MRI scans, AI systems can aid in the detection and classification of spinal pathologies. AI algorithms can assist radiologists and surgeons in identifying abnormalities, measuring parameters, and providing diagnostic support, potentially reducing interpretation errors and improving efficiency (16).

AI-powered real-time monitoring and decision support systems can enhance patient safety and surgical outcomes. By integrating data from various sources, such as intraoperative sensors, patient vital signs, and surgical parameters, AI algorithms can analyze the data in real-time and provide feedback and alerts to the surgical team. These systems can aid in identifying potential complications, guiding decision-making during surgery, and improving overall situational awareness (14).

The adoption of AI in spine surgery raises important ethical considerations. Privacy and security of patient data, transparency of AI algorithms, and the potential for biases in AI models are significant concerns (17). Ensuring patient consent, maintaining data integrity, and addressing the potential impact of AI on the surgeon-patient relationship are critical aspects to consider. Additionally, challenges related to regulatory approvals, integration of AI into clinical workflows, and liability in AI-driven decision-making need to be carefully addressed.

BIOMATERIALS AND TISSUE ENGINEERING

Utilization of biomaterials in regenerative spine surgery

Biomaterials play a crucial role in regenerative spine surgery by providing scaffolds, carriers, and therapeutic agents that facilitate tissue repair and regeneration. These materials are designed to mimic the natural properties of the extracellular matrix and create a favorable environment for tissue healing and integration (18). The utilization of biomaterials offers the potential to enhance the outcomes of spine surgeries by promoting tissue regeneration, reducing inflammation, and improving implant stability.

Bioactive scaffolds are designed to provide mechanical support to damaged or degenerated spinal tissues while promoting cellular infiltration, adhesion, and proliferation. These scaffolds often incorporate bioactive molecules, such as growth factors or extracellular matrix components, to enhance tissue regeneration and repair (19). They can facilitate cell attachment, migration, and differentiation, providing a conducive microenvironment for tissue healing.

Growth factors are potent signaling molecules that regulate various cellular processes involved in spinal fusion, such as osteogenesis and angiogenesis. In regenerative spine surgery, growth factors are often incorporated into biomaterials or delivered locally to stimulate bone formation and fusion (20). Growth factors, such as bone morphogenetic proteins (BMPs), can promote osteogenic differentiation of stem cells and enhance the formation of new bone tissue, leading to successful spinal fusion.

Stem cell therapies hold significant promise for functional recovery in spine surgery. Mesenchymal stem cells (MSCs) derived from various sources, such as bone marrow or adipose tissue, can differentiate into bone-forming cells, promote tissue regeneration, and modulate the inflammatory response (21). Stem cells can be delivered alone or in combination with biomaterials to promote spinal tissue regeneration, reduce scar formation, and potentially restore function.

Biomaterials and tissue engineering approaches have found clinical applications in various aspects of spine surgery, including intervertebral disc regeneration, spinal fusion, and spinal cord injury repair (19,20,21). Future prospects in this field include the development of advanced biomaterials with enhanced properties, the incorporation of bioactive molecules with controlled release kinetics, and the use of tissue engineering strategies to regenerate complex spinal tissues, such as the intervertebral disc or spinal cord.

Nanotechnology in Spine Surgery

Nanotechnology offers the potential to improve diagnostic capabilities in spine surgery through the development of nanoscale imaging tools. These tools can provide high-resolution imaging, enabling the detection of subtle structural abnormalities and pathological changes at the cellular or molecular level (22). Nanoparticles and nanosensors can be engineered to interact with specific targets, enhancing contrast and sensitivity in imaging modalities such as magnetic resonance imaging (MRI) or computed tomography (CT) scans.

Nanosensors hold promise for real-time monitoring of spinal conditions during surgery or postoperative recovery. These miniature devices can be designed to detect and measure various parameters, such as temperature, pH, pressure, or the presence of specific biomarkers (23). Nanosensors can provide valuable data on tissue status, implant integration, or infection, enabling timely intervention and personalized treatment approaches.

Nanotechnology enables the development of targeted drug delivery systems for spine surgery. Nanoparticles can be engineered to encapsulate drugs or therapeutic agents and deliver them directly to the desired site of action (24). This targeted approach improves drug efficacy, reduces systemic side effects, and enhances patient outcomes. Nanoparticles can be designed to release drugs in a controlled manner, ensuring sustained therapeutic effects and reducing the need for frequent dosing.

Nanotechnology has potential applications across various aspects of spine surgery. In addition to precise diagnostics and targeted drug delivery, nanomaterials can be utilized for tissue regeneration, spinal fusion enhancement, or prevention of implant-associated infections (25). However, several challenges need to be addressed for successful clinical translation. These challenges include safety concerns, biocompatibility of nanomaterials, regulatory approvals, scalability of production, and cost-effectiveness (25). Additionally, the long-term effects of nanomaterials on the human body and the potential for unintended consequences require thorough investigation.

Telemedicine and Remote Monitoring

Telemedicine has emerged as a valuable tool for postoperative care in spine surgery. Telemedicine platforms enable remote communication between patients and healthcare providers, allowing for virtual consultations, monitoring, and follow-up visits (26). Through telemedicine, patients can receive postoperative instructions, discuss their recovery progress, and address any concerns without the need for in-person visits. This enhances convenience, reduces travel requirements, and improves access to care, particularly for patients in remote or underserved areas.

Remote monitoring technologies have the potential to revolutionize real-time patient assessment in spine surgery. These technologies can include wearable devices, mobile health applications, or connected sensors that capture and transmit patient data, such as vital signs, physical activity, or medication adherence (26, 27). Remote monitoring enables healthcare providers to track patient progress, identify potential complications, and intervene promptly when necessary. It promotes early detection of issues and facilitates timely interventions, leading to improved patient outcomes.

Virtual follow-up visits through telemedicine platforms eliminate the need for patients to travel for in-person appointments, particularly for routine postoperative visits. This improves accessibility to specialized care, especially for patients who may face geographical or mobility challenges (26). Virtual visits allow patients to connect with their healthcare providers conveniently, discuss their recovery, review imaging results, and receive guidance on rehabilitation protocols. It also reduces the burden on healthcare facilities and allows for more efficient use of resources.

Telemedicine and remote monitoring can have a positive impact on patient outcomes and healthcare delivery in spine surgery. Studies have shown that telemedicine can lead to comparable patient satisfaction, reduced healthcare costs, and decreased readmission rates. Remote monitoring facilitates early identification of complications, enables timely intervention, and supports personalized care management, potentially leading to better clinical outcomes and improved patient experiences (28). Furthermore, the integration of telemedicine can optimize healthcare delivery, improve workflow efficiency, and enhance resource allocation.

Conclusion

The technological advancements discussed in this paper have the potential to shape the future of spine surgery in significant ways. Robotic-assisted surgery offers enhanced precision and improved outcomes through real-time guidance and surgical maneuver assistance. Augmented reality and virtual reality technologies provide valuable tools for preoperative planning, intraoperative navigation, and surgeon training. 3D printing and custom implants enable personalized treatment approaches, improved fit, and alignment. Artificial intelligence and predictive analytics offer decision support, precise diagnostics, and real-time monitoring. Biomaterials and tissue engineering approaches facilitate tissue regeneration and targeted drug delivery. Nanotechnology holds promise for precise diagnostics, real-time monitoring, and targeted therapies. Telemedicine and remote monitoring enhance postoperative care and improve accessibility to specialized care.

The potential impact of these advancements includes improved surgical outcomes, enhanced patient experiences, increased accessibility to specialized care, and optimized healthcare delivery. They have the potential to revolutionize surgical techniques, increase surgical precision, and promote personalized treatment approaches. These advancements can lead to better patient outcomes, reduced complications, and improved patient satisfaction.

However, challenges, limitations, and considerations must be addressed for successful implementation. These include the cost of adopting and maintaining new technologies, surgeon training and proficiency, regulatory approvals, privacy and security of patient data, standardization and quality control of new techniques, and addressing ethical considerations and potential biases. Additionally, scalability, integration into existing healthcare systems, and long-term effects on patients need to be carefully evaluated.

Future directions for research in spine surgery include further exploration of the potential of robotic-assisted surgery, refinement and advancement of augmented reality and virtual reality technologies, development of advanced biomaterials and tissue engineering strategies, exploration of new applications and nanomaterials, and ongoing evaluation of the impact of telemedicine and remote monitoring. Continued research and collaboration among surgeons, engineers, and scientists are crucial to advancing these technologies, addressing challenges, and optimizing their clinical applications.

In conclusion, the future of spine surgery is being shaped by technological advancements that offer improved precision, personalized treatment approaches, and enhanced patient outcomes. While challenges and considerations exist, the potential benefits are substantial. By continuing to innovate, collaborate, and address limitations, spine surgery can further evolve, providing better care for patients and advancing the field as a whole.

List of abbreviations

AR: Augmented Reality
VR: Virtual Reality
3D: Three Demential
CT: Computed Tomography
MRI: Magnetic Resonance Imaging
MSCs: Mesenchymal stem cells

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