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Commentary

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Spino-plastic surgery, back to the future

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Abstract

Artificial intelligence (AI) is a powerful computational tool that is being utilized more frequently in healthcare. AI holds promise within surgical practice, including application in the care of challenging patient populations. Complex spine reconstruction requires thorough multi-variable preoperative analysis and then the precise enactment of a surgical plan. Spino-plastics employs vascularized bone grafts (VBGs) to augment spinal fusion in these high-risk patients. In this article, we discuss the great breadth of AI and the tremendous potential for advancing the field of spino-plastics: surgical candidacy and patient selection, imaging and virtual surgical planning (VSP), intraoperative utilization, and future implementation.

Keywords: Artificial intelligence, spino-plastics, complex spinal reconstruction, machine learning, virtual surgical planning

INTRODUCTION

Artificial intelligence (AI) refers to computer systems that employ algorithms to analyze data, generate predictions, solve problems, and make decisions in a human-like fashion[1-3]. A range of technologies fall under the definition of AI, including machine learning (ML), deep learning (DL), natural language processing, and computer vision[2]. Given the immeasurable quantity of patient health data and increasingly advanced technologies capable of processing it, there are ample applications for AI in the spino-plastics domain[1].

Spino-plastic surgery is one surgical subspecialty that combines the talents of interdisciplinary surgical subspecialists within plastics, orthopedics, and neurosurgery to meet the needs of patients requiring complex spinal reconstruction. In brief, spino-plastics utilizes vascularized bone grafts (VBGs) from the iliac crest, spinous process, rib, scapula, clavicle, and occiput to augment the strength of spinal fusions necessitated by pathologies such as trauma, degeneration, or tumor[4-9]. VBGs are pedicled on muscle and supplied by Sharpey's fibers, which physically connect the muscle to bone and allow small unnamed periosteal feeding vessels to vascularize Haversian canals[10]. VBGs are increasingly indicated for the treatment of pseudoarthrosis, as they increase osteogenesis, osteoconductivity, and osteoinductivity compared to non-vascularized bone grafts (N-VBGs)[10]. Rates of pseudoarthrosis following arthrodesis can reach 60% or higher, leading to reoperations and significant morbidity that negatively impact quality of life[11,12]. VBGs have been incorporated into the existing reconstructive algorithm that is divided into six levels: allograft, bony substitution, autograft, N-VBG, VBG, pedicled vascularized bone flap, and free bone flap[10]. As VBGs have been found to enhance the strength of spinal fusion[13] and decrease rates of pseudoarthrosis, there is a need for an AI algorithm to identify those at risk for pseudoarthrosis who may benefit from VBG. Key areas of research interest within spino-plastics include the identification of optimal surgical candidates given the expanding indications for VBGs, as well as improving surgical techniques to enhance patient outcomes.

In the literature, there is already evidence of AI algorithms developed to screen for vulnerable patient populations and identify surgical candidates[1,3,14]. Furthermore, there are many existing AI algorithms with similar functions of patient risk stratification. Within spine surgery, AI has already been applied to identify surgical candidates and treatment options for anterior decompression and fusion for cervical spondylotic myelopathy[15,16], as well as to predict quality of life outcomes in adult spinal deformities[17]. The future of spine surgery may be guided by bioinformaticians, data engineers, and computer scientists who process big data in a way that informs patient care and scientific discovery[18]. In this article, we conducted a non-systematic narrative review of the literature to better understand AI's capability to transform the field of spino-plastics through assessment of surgical candidacy and patient selection, imaging and virtual surgical planning (VSP), and intraoperative instrument manipulation.

SURGICAL CANDIDACY AND PATIENT SELECTION

Disease classification systems are invaluable tools when applied appropriately within medical practice. While a classification score does not solely drive available treatment options, it is a standardized entry point and a piece to the overall puzzle in the care of patients with complex pathology. Unsupervised AI data analysis can create new hierarchical clustering that accounts for patient frailty scores, functional status, radiographic characteristics, and many demographic factors[19]. Sophisticated pattern analysis incorporates more data than could have been previously imagined, making surgeon education easier with elaborate risk-benefit grids for various treatment pathways[19].

Predictive algorithms are an excellent way to identify high-risk patients more effectively, such as those who are at a greater than average risk of pseudarthrosis, wound breakdown, or morbidity/mortality associated with spinal fusion. In general, earlier identification of high-risk patients allows for earlier intervention with proactive employment of strategies to mitigate the risks inherent to the patient or pathology itself. In spino-plastics specifically, this concept may be harnessed to identify patients who might benefit from a risk-reducing VBG and mitigate the consequences of debilitating pseudoarthrosis and failed spinal fusion. Given the current novelty of spino-plastic surgery, this information is currently unvalidated. AI and ML move beyond the traditional linear or logistic regression, incorporating greater dimensions of analysis to more accurately identify those who may benefit from VBGs and, therefore, bring novel prognostic indicators to light[20-22]. In spinal tumor surgery, which is a common indication for VBG, AI already has a role in patient risk stratification[23]. A Naïve Bayes ML algorithm developed by DiSilvestro *et al*. was better at predicting 30-day mortality following spinal tumor resection than the National Surgical Quality Initiative mortality probability calculator[24]. This algorithm is based on Bayes' theorem and predicts mortality based on independent patient risk factors. For example, this study found smoking, cancer, and chronic obstructive pulmonary disease to all be independent risk factors for 30-day mortality in intraspinal neoplasm excision. AI's role in predicting outcomes is a powerful tool that could similarly be harnessed in spino-plastics decision making.

Informed, shared decision making between the patient and provider fosters an atmosphere conducive to the best outcomes for everyone. ML eliminates barriers to the availability of high-powered data by generating accurate model populations that are based on groups of detailed, real patient data[25]. ML enhances understanding of the preoperative conditions and how this is likely to interact with desired surgical outcomes, effectively matching patients with the best available treatment options[26]. Combining physical exam findings or patient presentation with patient-specific anatomy in advanced imaging studies has the possibility to address healthcare disparities, improving access to care and creating a higher standard in fine-tuning preoperative patient selection[26]. In the context of spine surgery, one example of this concept in action is Wilson *et al*.'s AI model designed to predict when the degree of spinal stenosis by magnetic resonance imaging (MRI) requires specialist evaluation, streamlining subspecialty referrals for the benefit of earlier access to appropriate care and timely intervention[27].

Taking this one step further, ML can intelligently engineer algorithms that can achieve a high negative predictive value in determining the need for surgical intervention, possibly, and alternatively, higher risk situations, thereby amplifying vigilance toward those patients and redirecting the limited resources of office visits[28]. The quadruple aim of healthcare involves increasing patient and provider experience and improving population health while reducing overall healthcare costs[29]. AI utilization aligns well with the quadruple aim of healthcare by making the surgical triage experience more beneficial to all parties involved, increasing the ratio of surgical bookings to total patients seen in the clinic and improving the quality of care[28]. Overall, AI holds the potential to shift the paradigm of decision making in spine surgery.

IMAGING AND VSP

In addition to AI's contributions to surgical candidacy and patient risk stratification, its involvement in radiologic studies plays an integral role in several aspects of spine surgery. AI algorithms have already been developed to assist in the classification and localization of spinal tumors[30,31]. Zhuo *et al*. developed a DL model to classify spinal tumors using T2-weighted MRIs[30]. In a similar capacity, Liu *et al*. proposed a model utilizing a weighted fusion framework on MRI data to locate tumors and synthesize patient clinical information for more accurate tumor classification than doctors[31].

The automation of qualitative and quantitative radiologic interpretation promises advancement in volumetric assessments of tumors, determination of tumor genotype from phenotypic characteristics, disease or treatment burden on tumor-adjacent tissues, and much more[32]. As time progresses and technology improves, an increasing number of studies might attain results that reach clinical significance, with hopes of significant alterations to radiologic evaluation. For example, the important work of Wang *et al.* proved the clinical utility of applying deep neural networks for the detection of spinal metastasis, reaching an accuracy of 90%[33].

Specifically, within spino-plastics, there are many applications for AI in diagnostics and imaging. Spino-plastic reconstruction is concerned with (1) increased bony fusion, especially in the setting of previous failures; (2) decreased time to bony fusion; (3) optimizing the interface between soft tissues, hardware, and osseous structures in both form and skeletal function; (4) stable and long-term closure of wounds: these are data points that are amenable to AI application. As mentioned, there is a wide range of pathology warranting VBGs to augment spinal fusion, including prior failed fusion and extensive reconstruction after tumor extirpation. A closer and more comprehensive evaluation of radiologic studies might provide insight into patients that necessitate further intervention to offer a better chance at successful fusion. In addition, computer modeling based on multidimensional analysis of various imaging modalities might also propose the vertebral level incurring the greatest mechanical stress status post instrumentation and fusion[34], further aiding the surgical team in deciding the final target for VBG fixation.

This brings us to the discussion of VSP. This technique employs patient imaging to construct a 3D surgical model that allows for surgical simulation, visualization of complex anatomy, and virtual mapping to assist with procedural planning[35]. Over the past several decades, VSP has been widely adopted within orthognathic surgery, providing an alternative to traditional surgical planning techniques[36]. VSP improves surgical accuracy, creating more symmetry than would have otherwise been possible without this technology[36]. Therefore, VSP is trusted by orthognathic surgeons who operate in a field where aesthetic results are of paramount importance[36]. While there is still much room for growth in this surgical tool, it has been suggested that AI will only increase the scope of VSP[37]. In a recent 2023 study, Browd *et al.* describe how patient-specific quantitative metrics, such as bone density, sagittal balance, and Cobb angles, derived from imaging modalities can potentially be applied to AI and ML algorithms for better surgical planning[26].

INTRAOPERATIVE UTILIZATION

Intraoperatively, AI can be very helpful in tumor resection and reconstruction of the spine. For instance, AI can assist surgeons in differentiating between normal tissue and glioblastoma multiforme[38]. Alternatively, AI might be harnessed to improve existing technology and intraoperative decision making. Many devices and techniques have been described for improved intraoperative performance in spine surgery. Computer-assisted navigation systems such as stealth guidance assist in surgical planning and operational precision[23]. Stealth guidance is a robotic technology that enhances intraoperative localization and accuracy through three-dimensional modeling[39]. Stealth guidance systems such as Medtronic's StealthStation employ imaging data in the form of MRI and CT scans to create multidimensional anatomic models and real-time navigation that allows surgeons to know precisely where they are in space[40,41]. The precision enhancement of robotic-assisted stealth guidance has been demonstrated to reduce operative times and decrease intra- and postoperative complications in neurosurgical and spinal procedures requiring a higher level of dexterity and accuracy[42-44].

Another distinct piece of computer-assisted navigation systems that improve operative efficacy is augmented reality (AR). This technology assists with intraoperative navigation by overlaying graphics in the real world, enhancing the perception of surgical instruments in space[45,46]. By incorporating an overlay of surgical plans or highlighting relevant anatomy, surgeons are provided with real-time information that enhances their visualization and proprioception without the need to divert their attention away from the patient toward a screen[47]. AR has been integrated into fields like orthopedic surgery, trauma surgery, and spinal surgery to help with preoperative planning and surgical training[45,48]. The approach and positioning of pedicle screws, foraminotomies, percutaneous interventions, and biopsies can all be achieved more safely, with less margin of error, under the guidance of AR[49]. AR also permits spine surgeons to view dissection planes and tumor volumes with microscopic virtual mapping for performing osteotomies[50]. Ma *et al.* describe an ultrasound methodology to superimpose surgical planning *in situ* by incorporating CT images with 3D anatomic landmarks[51].

Spine surgery can be challenging at baseline, as it is not uncommon to lack direct exposure or visualization of the intricate, densely organized vessels and nerves along the axial skeleton. By the very nature of the field, spino-plastics aims to treat an even more challenging subsect of patients. The distortion of native anatomy in complex cases, whether caused by revision surgery or the mass effect of tumor bulk, presents additional obstacles to intraoperative identification of neurovasculature. AR can aid surgeons in this difficult task, employing visual information from MRI and CT scans to build surgical maps and chart paths around key anatomic structures[45,46]. In spino-plastics cases, once the spinal instrumentation and fusion are complete, the surgeon may harvest the VBG utilizing the standard arthrodesis instruments that are already on the sterile field. If stealth guidance or AR is already being utilized for arthrodesis, it would be wise to consider keeping the system available to assist the surgeon in harvesting and ensuring adequate fixation of the VBG. Better spatial conceptualization of the instrumentation might reduce any risk of damaging nearby structures in the vertebral column or retroperitoneum.

LOOKING TO THE FUTURE

Notably, the ultimate boundaries of AI have yet to be uncovered. AI has already contributed to our understanding of driver mutations behind spinal cord tumors[23]. This incredible technology will continue to improve basic science research and treatment modalities to address the needs of spino-plastic patients from many different perspectives. Despite the tremendous promise and exponential rise in these technological advancements, there is much work to be done before clinicians may be completely comfortable about incorporating this new technology into their workflow. Because ML is a powerful tool that is not fully understood, caution must be exercised regarding the input of information to avoid the perpetuation of misinformation and social biases. Overall, ML and AI currently lack transparency, which creates a "black box" that may be difficult for surgeons to trust when comparing results to well-published algorithms that have a more easily understood basis. However, there are methods currently being utilized to validate their efficacy in clinical practice. This includes the results of case studies and trials - where technologies such as imaging guidance can differentiate tumors from healthy tissue[52] - comparative studies, and live integration with surgical teams[3] that provide constant feedback to enhance the safety and predictive power of AI algorithms. Many metrics were used in these various studies to compare the performance of AI algorithms to traditional models, such as the area under the curve, accuracy, and the receiver operating characteristic curve. Furthermore, there is an upfront investment of time and resources essential for the development of novel algorithms bearing any clinical significance. In other words, there is a significant lag time between technological advancements and gaining necessary approvals for clinical application through the proper avenues, including national supervisory organizations and individual hospital systems[53]. In this stage of conceptualization, there are limited existing data on AI in spino-plastic surgery and further long-term data collection is required.

Despite the harvest and fixation of VBGs not requiring any additional tools that are traditionally used in spinal fusion, the field of spino-plastics is in its nascent stages. Due to resource limitations or surgeon-specific comfort levels with working in the spine and retroperitoneum, not all institutions have access to plastic surgeons capable of performing this procedure. Developing strategies to implement novel AI technologies beyond academic practice, particularly in rural communities, is essential to ensuring equity in an increasingly digital age. Research has already discussed several key strategies, including improving digital infrastructure, such as internet access, and networks of local health information that can be employed to train AI. Training local community healthcare workers to utilize novel technologies such as mobile health applications and engaging with community stakeholders to determine the most impactful implementation strategies are also crucial[54].

CONCLUSION

Spino-plastics uses a long-standing well-accepted concept of VBGs and applies it to quite complex reconstructive problems. Innovation is at the heart of this field, and spine surgeons are no strangers to welcoming new technologies and techniques. AI holds great promise in advancing medicine overall, making data collection and processing easier than ever with seemingly unending applications for the delivery of patient care. Beyond its potential role in patient selection, the visual enhancement offered by AI technologies can assist in diagnostics, surgical planning, and intraoperative precision. Spinal tumor resection often results in complex spinal defects that are nonuniform and in close proximity to several critical structures. In the planning and intraoperative phases, AI can improve outcomes by enhancing the accuracy of instrument movements and assisting with surgical planning and decision making[55,56]. When AI is used in conjunction with other advanced technologies such as AR or stealth guidance, three-dimensional visualization is further enhanced, reducing risks of intraoperative complications[45]. Thus, AI may one day function as a spino-plastic surgeon's first assistant in future operating rooms. Spinal fusion calls for advancements and synergy in AI, robotics, and AR. There is great promise in the collaborative opportunities that telemedicine and telesurgery will bring, dismantling the geographic and socioeconomic barriers to centers of excellence in multidisciplinary care[25]. In conclusion, the integration of AI into spino-plastic surgery not only has the power to further individualize and enhance VBG's precision and effectiveness, but also broaden their potential indications, ultimately transforming the landscape of complex spinal reconstruction and offering new possibilities for patient care.

DECLARATIONS

Authors' contributions

Drafted this original manuscript: Martinez C, Payne C, Jeger JL, Van Spronsen N

Conceptualized and edited this manuscript: Winocou S, Kalani MA, Bohl M, Ropper AE, Reece EM

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Consent for publication

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