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Invited Review

Personalizing adult spinal deformity surgery through multimodal artificial intelligence

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ABSTRACT

To achieve meaningful, patient-centered outcomes following adult spinal deformity (ASD) surgery, it is crucial to engage in precise preoperative planning, perform excellent intraoperative execution, and ensure careful postoperative management. The field of multimodal artificial intelligence (AI) is rapidly developing and should be integrated into the management of ASD patients. In this context, we outline the current concepts and explore future applications of AI across the ASD care continuum.

Introduction

Well-indicated adult spinal deformity (ASD) surgery improves patient-reported outcomes (PROs) and health-related quality of life.[1,2] While ASD surgery is experiencing ongoing improvement and innovation,[3] it remains challenging to achieve excellent PROs while mediating complications and suboptimal outcomes.[4] The costs, direct and indirect, to patients, families, and society are consequential when ASD surgery outcomes are poor and complications occur.

Advances in computing, algorithmic design, and data availability have aligned to bring marked advances in artificial intelligence (AI) to bear on healthcare. Recently, there have been advances in multimodal AI for medicine, expanding AI tools beyond classic tabular data[5-7] to integrate diverse data types such as radiographic imaging,[8,9] physiologic waveform data,[10] and surgical video.[11] Given the significant consequences of ASD surgery, it is imperative that these tools are leveraged in the preoperative, intraoperative, and postoperative periods.[12] In this narrative review, we outline early work applying AI along the care spectrum of ASD and suggest future areas of research and innovation.

Preoperative period—patient selection and optimization

Appropriate patient selection for ASD surgery requires clinical judgment that classically comes only with time and experience. Understanding when *not* to operate may be more challenging than understanding when to offer surgery. Moreover, even the most experienced spinal deformity surgeon will not be able to predict each patient's outcome with complete accuracy. Predictive modeling has emerged as an early form of decision support to augment risk stratification and enable better patient counseling.[13] Current ASD prediction models have largely used tabular data.[14] One such prediction approach uses unsupervised machine-based clustering to uncover potential ASD patient "groups" that differ by patient baseline or pathology characteristics.[6] The predictive power of these models will be improved when diverse data types are incorporated. These may include biomarkers of frailty and senescence, radiomics, and objective markers of phenotype.[15] Smartphones and wearable devices are also a growing source of functional health data, providing a natural and continuous method for ASD patient metrics to be recorded and characterized within a "digital phenotype."[16,17]

More abundant and diverse data through wearable technologies and multiple points of assessment will allow for the assessment of predictive power via area under the curve analysis. With greater predictive power, it will be important to develop novel approaches for preoperative optimization. Artificial intelligence-assisted optimization may allow patients who would have previously not been selected for surgery due to medical contraindications to be operated on without significant risk. For example, a patient with a high preoperative risk of mechanical complications[18] following ASD surgery can undergo further testing to understand their musculoskeletal health and receive targeted prehabilitation and multi-disciplinary medical optimization. Similarly, a patient at high preoperative risk for significant blood loss[19] can be counseled specifically and the anesthesia team can prepare appropriately. Rather than the standard decision-making approach of "operate" versus "not operate," AI can expand preoperative patient selection to classify patients as "operate as-is," "operate after optimization," and "not operate." This strategy has

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the potential to offer ASD surgery to a wider breadth of patients and reduce surgery-associated morbidity for those ultimately selected.

Preoperative period—assistance with operative planning

Once the decision to operate has been made, AI can assist surgeons during preoperative procedure planning. Prior work includes models that analyze spinal radiographic parameters such as kyphosis or pelvic tilt in ASD patients, which in turn can help the surgeon determine ideal surgical approaches or end-points.[20] One study further constructed a neural network to predict upper instrumented vertebrae levels for ASD patients, and the model displayed comparable decision-making to experienced human surgeons.[21] AI has also been used to assist with instrument use, as in the case of model-assisted pedicle screw length and diameter selection based on patients' computed tomography images.[22] The preoperative implementation of AI in this way can help surgeons save time and serve as a confirmatory adjunct to their own expertise during the complex ASD surgery planning stages. With further advancement of these technologies, it is possible that computer simulations could model the expected postoperative anatomy after incorporating these AI-generated preoperative parameters and recommended surgical techniques. The ideal surgical specifications and subsequent results could therefore be predicted with a high degree of certainty from a patient's radiographic studies alone.

Intraoperative period—decision support and performance assessment

Multiple enabling technologies that use AI have emerged for intraoperative assistance in ASD surgery. Although they are largely limited to pedicle screw placement, various intraoperative adjuncts such as robotics,[23,24] navigation,[25] and augmented reality[26] bring AI into the operating room. Advances in algorithms and imaging may result in enabling technologies for osteotomy execution, interbody placement, and deformity correction maneuvers. Patient-specific rods, pre-emptively contoured to a preoperative correction plan,[27] are a recent innovation that hints at a future of personalized ASD surgery. Machine learning models have also demonstrated the ability to intraoperatively predict the degree of spinal reciprocal compensation that occurs due to ASD surgery.[28,29] Further future applications of AI decision-support in ASD surgery include personalized blood transfusion and fluid resuscitation as well as predictive neuromonitoring.

As multimodal generative AI further develops, it is wholly possible that real-time intraoperative assistance will be enabled. The next step may be an automated intraoperative reconciliation process that evaluates the surgeon's operative progress as it occurs and compares it to the preoperative plan. This may allow for corrections of surgical errors or evaluation of sub-optimal surgical plans prior to the end of the procedure. Another development could be an AI-assisted surgical "co-pilot." This could augment the surgeon's capabilities by using computer vision, integrated with preoperative imaging, to allow better visualization and illumination. The co-pilot could be integrated with sensors in the surgeon's gloves to enhance haptic feedback. A truly advanced multimodal AI surgical co-pilot may enable real-time rehearsal of complex osteotomies or correction maneuvers by generating a brief video of the planned maneuver for the surgeon to review prior to execution.

Postoperative period—medical management and complication mitigation

To date, there has been limited focus on AI-augmented postoperative care of ASD patients. However, after large ASD correction, better biomarkers of resuscitation status may enable patient-specific, goal-directed postoperative care. Artificial intelligence-enabled intensive care units, where algorithms parse high-density physiologic waveform data, will likely enable earlier prediction and treatment of immediate postoperative complications.[30] Using preoperative, intraoperative, and early postoperative data, AI models may also be trained to predict patients' functional outcomes with different treatment regimens. Yet, this is likely to be a complex task, as postoperative complications for ASD patients have been shown to be related to changes at the biomolecular level.[31,32] Artificial intelligence predictions may improve slightly with more patient data, but "deep phenotyping" of ASD patients is likely also needed to form accurate predictions.

Full care continuum—large language models for patient guidance

Artificial intelligence is also well-positioned to serve as a care navigator for patients with ASD. Large language models (LLMs, e.g., ChatGPT) have shown utility in informed consent for surgery, potentially reducing jargon and improving patient understanding by generating simplified documents.[33,34] Large language models have also demonstrated proficiency in answering potential patient questions about spine pathology and surgery.[35] As patients can access LLMs from the comfort of their own home, there would be no time restraint for which questions about their condition or upcoming surgery could be answered.[36] Moreover, an LLM fine-tuned to a surgeon's postoperative recommendations could readily answer patient questions on demand and may enhance compliance with postoperative instructions. Although LLMs cannot currently replace the expertise of an experienced spine surgeon, these benefits suggest that LLMs may eventually serve to mitigate logistical challenges in the preoperative and postoperative education of ASD patients. Further LLM training over time will improve their clinical acumen and ability to assist in the care of patients with various spine pathologies.

Conclusion

Achievement of successful, patient-centric outcomes in ASD surgery requires nuanced decision-making throughout the care continuum. Multimodal AI holds the potential to significantly improve this process.

HIGHLIGHTS

- Artificial intelligence (AI) technology can assist spine surgeons before, during, and after adult spinal deformity (ASD) correction procedures.
- Artificial intelligence may be applied to identify ideal ASD surgical candidates and has the potential to predict outcomes.
- There is significant growth potential for AI in ASD surgery, particularly for its uses within the intraoperative period.
- Artificial intelligence assistance in ASD surgery can be further strengthened by incorporating diverse data such as patients' "digital phenotype" and biomolecular profile.

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