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Review

Machine Learning Applications in Adult Spinal Deformity Corrective Surgery: A Narrative Review

Nader Toossi[1]*, Ozhan Jerry[2]

[1]Musculoskeletal Education and Research Center, Audubon, PA, USA.

[2]Department of Surgery, Pennsylvania State University, Pennsylvania, PA, USA.

***Correspondence to**: Dr. Nader Toossi, Musculoskeletal Education and Research Center, Clinical Research, Audubon, PA, USA. E-mail: nt392@drexel.edu.

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ABSTRACT

Adult Spinal Deformity (ASD) poses significant challenges in spinal surgery, requiring precise planning and execution for successful correction. Also, optimization of outcomes and reducing the high complication rates of ASD surgeries are additional challenges facing spinal deformity surgeons. The advent of machine learning (ML) has revolutionized various aspects of healthcare, including spinal surgery. This review provides a comprehensive overview of the current state of ML applications in spinal deformity corrective surgery, highlighting its potential benefits and challenges.

Keywords: machine learning, adult spinal deformity, predictive modeling, artificial intelligence

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INTRODUCTION

With the aging population, the incidence and prevalence of Adult Spinal Deformity (ASD) are on the rise[1], affecting millions worldwide and significantly impacting their quality of life. This often leads to the necessity of complex surgical interventions. Planning ASD surgery involves evaluating not only the entire spinal column but also the entirety of the skeleton to ensure appropriate radiographic alignment. ASD patients present with a variety of heterogeneous clinical manifestations, and there is a vast array of surgical methods available for their treatment, making the treatment algorithm quite complex. Additionally, ASD surgery is associated with high complication rates in both the short and long term. These observations make ASD an ideal candidate for leveraging the significant potential offered by artificial intelligence and machine learning (ML).

Computational techniques have been used in the past several years to process large datasets and create complex mathematical models to determine the relationship between different variables affecting the outcomes of surgery. The idea behind ML, a subset of artificial intelligence, is to develop a system similar to human brain to learn from the clinical and radiographic data and apply the knowledge to new situations. In other words, ML employs computer algorithms to learn from data and past experiences, enabling the creation of intelligent models. These algorithms enable computers to identify patterns in datasets without relying on predefined rules, allowing them to learn relationships from the data and make predictions or decisions based on that knowledge. It has been shown that validated ML risk calculators can provide more accurate and objective prognosis to adjust patient expectations during patient care than expert surgeon's perception of risks in ASD surgery[2]. The development of predictive models via ML algorithms for prognosticating patient outcomes following ASD surgery represent a significant advancement over traditional statistical models, which are more adept at identifying statistical associations between variables rather than providing predictive value[3].

ML has shown promise in enhancing the accuracy and efficiency of various medical procedures, including spinal surgery. By taking advantage of large datasets and advanced algorithms, ML can assist surgeons in preoperative planning, intraoperative decision-making, and postoperative care, leading to improved patient outcomes.

The aim of this narrative review is to provide an overview of the current status of ML in enhancing spinal deformity correction surgery and its applicability in preplanning, intraoperative guidance, predictive modeling, and postoperative risk assessment.

METHODOLOGY

The authors conducted a non-systematic review of recent literature to support their perspectives on the applicability of ML in corrective spine surgery for adult ASD. This narrative review addresses three key stages in surgical practice where ML can be impactful and concludes by discussing the major challenges and future directions in the field.

PREOPERATIVE PLANNING

Appropriate preoperative patient selection significantly impacts patient satisfaction, individualized decision-making by surgeons, and hospital resource utilization. Identifying patients with favorable outcomes preoperatively is a challenging task. Traditional statistical methods, such as multiple regression analyses, are better suited for hypothesis testing rather than predicting individual patient outcomes. In contrast, machine learning algorithms can readily identify patterns within large datasets without the need to test a specific hypothesis[4]. However, this advantage of ML algorithms comes at the cost of interpretability. Predictive models generated by ML are more difficult to interpret than risk factors identified by traditional statistical tests[3].

ASD patients exhibit significant heterogeneity in demographics, comorbidities, spinal pathologies, and genetic factors. Traditional outcome predictive models often overlook

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these individual variabilities, leading to suboptimal predictions. However, machine learning models excel in accounting for these differences. By analyzing comprehensive datasets that include detailed individual patient profiles, these models can generate personalized predictions, enhancing clinical decision-making and patient outcomes.

ML algorithms can analyze preoperative imaging studies, such as X-rays, CT scans, and MRI scans, to provide detailed insights into the patients' spinal alignments[5-7].This includes assessing the degree of deformity, identifying critical structures, and predicting the optimal surgical approach[8]. ML models can also assist in selecting the appropriate implants (like pre-bent patient-specific rods) and predicting the postoperative spinal alignment, helping surgeons customize their surgical plan for each patient[9,10]. Using ML algorithms, a group of investigators could accurately predict spinopelvic parameters and thoracic kyphosis after deformity correction surgery[11]. ML models can preoperatively be used to estimate the likelihood of extended length of stay following ASD surgery[12,13]. Thus the surgeon can optimize modifiable risk factors, enhance preoperative planning and manage patients' expectations. Other investigators have developed predictive models to estimate the risk of rehabilitation discharge for adult patients undergoing elective surgeries including ASD patients[14].

Lafage et al. used artificial neural network based on preoperative data and alignment goals to accurately (81%) predict the upper instrumented vertebra (UIV) in a series of ASD patients. This study showed how "to employ a neural network to mimic surgeon decision making for UIV selection"[15]. Also, prognosis can be predicted by using ML algorithm to identify different patient phenotypes preoperatively. In a recent prospective multi-center study on 570 ASD patients conducted by European and US-based Spine Study Group, investigators could identify three different qualitative preoperative phenotypes in ASD patients based on demographics, surgical history, frailty, radiographic measures, patient-reported outcome measures. These phenotypes had been identified through unsupervised machine-based clustering. Based on these

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phenotypes, one can augment preoperative decision-making, predict the clinical outcome of deformity surgery (prognostic values) and tailor treatment approaches[16].
An international team of researchers used a predictive ML model preoperatively to predict the individual answers to the Scoliosis Research Society-22R (SRS-22R) questionnaire at 1 and 2 years after ASD surgery. This prediction provides the patients with reasonable preoperative counseling based on their expectations and perceptions of the corrective surgery clinical outcomes[17]. Mekhael et al. used a random forest ML model to accurately predict health-related quality of life outcomes after ASD surgery. They found that three-dimensional movement assessment of ASD patients can better predict clinical outcomes than stand-alone radiographic parameters, not only for physical but also for mental scores[18]. In another study, the researchers used a “machine learning model based on random forest regression and a systematic decision tree-like approach” to predict health-relate quality of life scores, gait kinematics, and spatial-temporal parameters based on radiographic global alignment parameters[19]. They found that Global Sagittal Angle[20] and T9 tilt[21] were the best predictor of joint kinematics and health -related quality of life scores.

Conditional inference tree run ML analysis was used to identify baseline threshold for different radiographic parameters to achieve a good outcome following ASD surgery. These parameters were: sagittal vertical axis, pelvic incidence–lumbar lordosis mismatch, pelvic tilt, T1 pelvic angle, L1 pelvic angle, L4–S1 lordosis, C2–C7 sagittal vertical axis, C2–T3, C2 slope[22].

Aiming to preoperatively predict proximal junctional kyphosis (PJK) after ASD corrective surgery, a team of researchers included preoperative thoracic T1 MRIs in a deep learning ML model (convolutional neural network) to increase the accuracy of the prediction[23]. Using a large prospective multi-center database, a group of investigators constructed a supervised ensemble of decision trees to preoperatively predict the risk of pseudarthrosis at 2 years after ASD surgery with 91% of accuracy[24].

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INTRAOPERATIVE GUIDANCE

During surgery, ML algorithms can provide real-time guidance to surgeons, enhancing the accuracy of instrument placement and the overall surgical technique. By integrating with navigation systems, ML can track the position of surgical instruments relative to the patient's anatomy, ensuring precise correction of spinal deformity. Using ML methodology, Burstrom et al. were able to accurately place pedicle screws during CT-based navigation[25]. Preplanning the pedicle screw trajectory using ML system has yielded highly accurate results[26]. ML can also be used to analyze intraoperative data, such as neuromonitoring signals, to alert surgeons of potential complications, such as nerve injury, enabling prompt intervention. Real-time automated decision-making systems regularly integrate inputs from intraoperative neuromonitoring and the operating room environment, utilizing predictive models to generate instructions or warnings for the surgical team. These systems continuously update their predictive models and decision-making processes based on new data and feedback from the surgeon and neurophysiologist, ensuring adaptive and accurate responses during surgery[27].

By using perioperative data, ML-based risk calculators can predict the 30-day complication and mortality risk following ASD corrective surgery[28]. Kim et al. could use ML algorithms to predict mortality and medical complications following ASD surgery. Using a large national database, they found that ML algorithms outperformed American Society of Anesthesiologists scoring in predicting individual risk prognosis[29].

Using conditional inference tree analysis (a ML-based method), a team of investigators could predict blood loss and perioperative blood transfusion in ASD patents undergoing surgery[30]. The artificial neural network was used to predict perioperative blood transfusion after ASD corrective surgery with 81% accuracy[31]. Also, another group of researchers found no difference between random forest and tree-based ML models to predict blood transfusion following ASD corrective surgery[32].

A team of researchers used ML-based predictive models to predict the likelihood of overall and over minimal clinically important difference (MCID) improvement following ASD surgery and tested with eight patient-reported outcome measure instruments. The models could predict accurately and consistently if a procedure will achieve MCID for a given patient using a given outcome instrument across a given time interval[33,34].

POSTOPERATIVE CARE

After ASD surgery, ML can aid in monitoring patients' recovery and predicting potential complications. By analyzing postoperative imaging[35] and clinical data, ML models can identify early signs of implant failure, infection, or other complications, allowing for timely intervention[36]. Since ASD surgery is fraught with complications postoperatively, many different characterizations have been developed to predict the complications after the surgery or determine risk profiles for development of complications following deformity correction. The success of computer vision, large language models and genome-wide association (incorporating advanced machine learning technologies) in a cohort of ASD patient in predicting various complications has been shown recently by a group of investigators[37]. Major medical complications, discharge to a facility and 90-day readmission were predicted using ML methods with decent accuracy[38,39].

ML can also assist in predicting long-term complications, such as the risk of adjacent segment degeneration and PJK, and helping surgeons and patients make informed decisions about follow-up care. Korean investigators recently developed and verified an online calculator for predicting PJK risk following ASD surgery using a machine learning model. They based their study on the radiographic outcomes obtained from 16 surgical centers[40]. Also, to predict mechanical complications following ASD surgery, some investigators tried different ML models and found that random forest had the best prediction accuracy of 73.2%[41]. Also, in a postoperatively well-aligned patient group following ASD surgery, some researchers could predict the mechanical complications with moderate accuracy (74%) using extreme gradient boosting ML algorithms. The mechanical complications investigated were: proximal junctional kyphosis and failure, distal junctional kyphosis and failure, rod breakage, and implant-related complications[42]. Lovecchio et al.[43] used decision tree analysis to predict the risk of proximal junctional failure and PJK by studying pre-discharge standing radiographs of ASD patients.

A group of Korean investigators could identify risk factors for unplanned readmission after ASD and predict it using a ML model[44]. Some researchers used a conditionally unbiased regression tree and random forest algorithm to predict cost outliers in ASD correction up to 2 years after the index surgery[45].

Challenges and Future Directions

Despite its potential benefits, the integration of ML into spinal deformity correction surgery faces several challenges. These include the need for large, high-quality datasets, the interpretability of ML models, and the ethical and regulatory implications of ML algorithmic decision-making[46,47]. Some investigators have suggested using biologic samples (muscle and bone sampling, assessment of circulating biomarkers,…) to improve the accuracy of ML predictions in the future[48,49].Also, most current studies employ random split approach, in which the majority (70%–90%) of the available data are used for training the model, while the remaining 10%–30% for testing its performance. This approach is not generally deemed sufficient for the aim of “external” validation[50]. Also, the extent to which ML-based predictions meaningfully affect clinical decisions and practices in real life has yet to be investigated. Future research should focus on addressing these challenges, as well as exploring new applications of

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ML, such as personalized surgical planning and robotic-assisted surgery, to further improve patient outcomes.

CONCLUSION

ML has the potential to revolutionize spinal deformity correction surgery by enhancing preoperative planning, intraoperative guidance, and postoperative care. By leveraging the power of large datasets and advanced algorithms, ML can assist surgeons in achieving more precise and personalized surgical outcomes, ultimately benefiting patients with spinal deformities.

DECLARATIONS

Authors' contributions

Made substantial contributions to conception and design of the study and drafted the manuscript: Toossi N.

Performed literature search, as well as provided administrative, technical, and material support: Jerry O.

Availability of data and materials

Not applicable.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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REFERENCE

1. Schwab F, Dubey A, Gamez L, et al. Adult Scoliosis: Prevalence, SF-36, and Nutritional Parameters in an Elderly Volunteer Population. *Spine* 2005;30:1082-5. DOI: 10.1097/01.brs.0000160842.43482.cd

2. Pellise F, Vila-Casademunt A, Nunez-Pereira S, et al. Surgeons' risk perception in ASD surgery: The value of objective risk assessment on decision making and patient counselling. *Eur Spine J* 2022;31:1174-83. DOI: 10.1007/s00586-022-07166-2

3. Joshi RS, Lau D, Scheer JK, et al. State-of-the-art reviews predictive modeling in adult spinal deformity: applications of advanced analytics. *Spine Deform* 2021;9:1223-39. DOI: 10.1007/s43390-021-00360-0

4. Akosman I, Lovecchio F, Lyons K, et al. The emerging role of artificial intelligence in adult spinal deformity. *Semin Spine Surg* 2022;34:100986. DOI: 10.1016/j.semss.2022.100986

5. Haselhuhn JJ, Soriano PBO, Grover P, et al. Spine surgeon versus AI algorithm full-length radiographic measurements: a validation study of complex adult spinal deformity patients. *Spine Deform* 2024. DOI: 10.1007/s43390-024-00825-y

6. Harake ES, Linzey JR, Jiang C, et al. Development and validation of an artificial intelligence model to accurately predict spinopelvic parameters. *J Neurosurg Spine* 2024:1-9. DOI: 10.3171/2024.1.SPINE231252

7. Suri A, Tang S, Kargilis D, et al. Conquering the Cobb Angle: A Deep Learning Algorithm for Automated, Hardware-Invariant Measurement of Cobb Angle on Radiographs in Patients with Scoliosis. *Radiol Artif Intell* 2023;5:e220158. DOI: 10.1148/ryai.220158

8. Galbusera F, Niemeyer F, Wilke HJ, et al. Fully automated radiological analysis of spinal disorders and deformities: a deep learning approach. *Eur Spine J* 2019;28:951-60. DOI: 10.1007/s00586-019-05944-z

9. Faulks CR, Biddau DT, Munday NR, et al. Patient-specific spinal rods in adult spinal deformity surgery reduce proximal junctional failure: a review of patient outcomes and surgical technique in a prospective observational cohort. *J Spine Surg* 2023;9:409-21. DOI: 10.21037/jss-23-85

10. Picton B, Stone LE, Liang J, et al. Patient-specific rods in adult spinal deformity: a systematic review. *Spine Deformity* 2024. DOI: 10.1007/s43390-023-00805-8

11. Lee NJ, Sardar ZM, Boddapati V, et al. Can Machine Learning Accurately Predict Postoperative Compensation for the Uninstrumented Thoracic Spine and Pelvis After Fusion From the Lower Thoracic Spine to the Sacrum? *Global Spine J* 2022;12:559-66. DOI: 10.1177/2192568220956978

12. Arora A, Demb J, Cummins DD, et al. Predictive models to assess risk of extended length of stay in adults with spinal deformity and lumbar degenerative pathology: development and internal validation. *Spine J* 2023;23:457-66. DOI: 10.1016/j.spinee.2022.10.009

13. Li W, Zhang Y, Zhou X, et al. Ensemble learning-assisted prediction of prolonged hospital length of stay after spine correction surgery: a multi-center cohort study. *J Orthop Surg Res* 2024;19:112. DOI: 10.1186/s13018-024-04576-4

14. Arora A, Lituiev D, Jain D, et al. Predictive Models for Length of Stay and Discharge Disposition in Elective Spine Surgery: Development, Validation, and Comparison to the ACS NSQIP Risk Calculator. *Spine (Phila Pa 1976)* 2023;48:E1-E13. DOI:

10.1097/BRS.0000000000004490
15. Lafage R, Ang B, Alshabab BS, et al. Predictive Model for Selection of Upper Treated Vertebra Using a Machine Learning Approach. *World Neurosurg* 2021;146:e225-e32. DOI: 10.1016/j.wneu.2020.10.073
16. Mohanty S, Hassan FM, Lenke LG, et al. Machine learning clustering of adult spinal deformity patients identifies four prognostic phenotypes: a multicenter prospective cohort analysis with single surgeon external validation. *Spine J* 2024. DOI: 10.1016/j.spinee.2024.02.010
17. Ames CP, Smith JS, Pellise F, et al. Development of predictive models for all individual questions of SRS-22R after adult spinal deformity surgery: a step toward individualized medicine. *Eur Spine J* 2019;28:1998-2011. DOI: 10.1007/s00586-019-06079-x
18. Mekhael E, El Rachkidi R, Saliby RM, et al. Functional assessment using 3D movement analysis can better predict health-related quality of life outcomes in patients with adult spinal deformity: a machine learning approach. *Front Surg* 2023;10:1166734. DOI: 10.3389/fsurg.2023.1166734
19. Nassim N, Mekhael E, Rachkidi RE, et al. Global Sagittal Angle and T9-tilt seem to be the most clinically and functionally relevant global alignment parameters in patients with Adult Spinal Deformity. *Brain and Spine* 2024;4:102805. DOI: 10.1016/j.bas.2024.102805
20. Diebo BG, Oren JH, Challier V, et al. Global sagittal axis: a step toward full-body assessment of sagittal plane deformity in the human body. *J Neurosurg Spine* 2016;25:494-9. DOI: 10.3171/2016.2.SPINE151311
21. Legaye J, Duval-Beaupere G. Sagittal plane alignment of the spine and gravity: a radiological and clinical evaluation. *Acta Orthop Belg* 2005;71:213-20
22. Williamson TK, Krol O, Tretiakov P, et al. Crossing the Bridge From Degeneration to Deformity: When Does Sagittal Correction Impact Outcomes in Adult Spinal Deformity Surgery? *Spine* 2023;48:E25-E32. DOI: 10.1097/brs.0000000000004461
23. Johnson GW, Chanbour H, Ali MA, et al. Artificial Intelligence to Preoperatively Predict Proximal Junction Kyphosis Following Adult Spinal Deformity Surgery: Soft Tissue Imaging May Be Necessary for Accurate Models. *Spine* 2023;48:1688-95. DOI: 10.1097/brs.0000000000004816
24. Scheer JK, Oh T, Smith JS, et al. Development of a validated computer-based preoperative predictive model for pseudarthrosis with 91% accuracy in 336 adult spinal deformity patients. *Neurosurg Focus* 2018;45:E11. DOI: 10.3171/2018.8.FOCUS18246
25. Burstrom G, Buerger C, Hoppenbrouwers J, et al. Machine learning for automated 3-dimensional segmentation of the spine and suggested placement of pedicle screws based on intraoperative cone-beam computer tomography. *J Neurosurg Spine* 2019;31:147-54. DOI: 10.3171/2018.12.SPINE181397
26. Siemionow KB, Forsthoefel CW, Foy MP, et al. Autonomous lumbar spine pedicle screw planning using machine learning: A validation study. *J Craniovertebr Junction Spine* 2021;12:223-7. DOI: 10.4103/jcvjs.jcvjs_94_21
27. Wilson Jr JP, Kumbhare D, Kandregula S, et al. Proposed applications of machine learning to intraoperative neuromonitoring during spine surgeries. *Neuroscience Informatics* 2023;3:100143. DOI: 10.1016/j.neuri.2023.100143
28. Pierce KE, Kapadia BH, Naessig S, et al. Validation of the ACS-NSQIP Risk Calculator: A Machine-Learning Risk Tool for Predicting Complications and Mortality Following Adult Spinal

Deformity Corrective Surgery. *Int J Spine Surg* 2021;15:1210-6. DOI: 10.14444/8153
29. Kim JS, Arvind V, Oermann EK, et al. Predicting Surgical Complications in Patients Undergoing Elective Adult Spinal Deformity Procedures Using Machine Learning. *Spine Deform* 2018;6:762-70. DOI: 10.1016/j.jspd.2018.03.003
30. Raman T, Vasquez-Montes D, Varlotta C, et al. Decision Tree-based Modelling for Identification of Predictors of Blood Loss and Transfusion Requirement After Adult Spinal Deformity Surgery. *Int J Spine Surg* 2020;14:87-95. DOI: 10.14444/7012
31. De la Garza Ramos R, Hamad MK, Ryvlin J, et al. An Artificial Neural Network Model for the Prediction of Perioperative Blood Transfusion in Adult Spinal Deformity Surgery. *J Clin Med* 2022;11. DOI: 10.3390/jcm11154436
32. Durand WM, DePasse JM, Daniels AH. Predictive Modeling for Blood Transfusion After Adult Spinal Deformity Surgery: A Tree-Based Machine Learning Approach. *Spine (Phila Pa 1976)* 2018;43:1058-66. DOI: 10.1097/BRS.0000000000002515
33. Ames CP, Smith JS, Pellise F, et al. Development of Deployable Predictive Models for Minimal Clinically Important Difference Achievement Across the Commonly Used Health-related Quality of Life Instruments in Adult Spinal Deformity Surgery. *Spine (Phila Pa 1976)* 2019;44:1144-53. DOI: 10.1097/BRS.0000000000003031
34. Patel AV, White CA, Schwartz JT, et al. Emerging Technologies in the Treatment of Adult Spinal Deformity. *Neurospine* 2021;18:417-27. DOI: 10.14245/ns.2142412.206
35. Lochel J, Putzier M, Dreischarf M, et al. Deep learning algorithm for fully automated measurement of sagittal balance in adult spinal deformity. *Eur Spine J* 2024. DOI: 10.1007/s00586-023-08109-1
36. Hopkins BS, Mazmudar A, Driscoll C, et al. Using artificial intelligence (AI) to predict postoperative surgical site infection: A retrospective cohort of 4046 posterior spinal fusions. *Clin Neurol Neurosurg* 2020;192:105718. DOI: 10.1016/j.clineuro.2020.105718
37. Schonfeld E, Pant A, Shah A, et al. Evaluating Computer Vision, Large Language, and Genome-Wide Association Models in a Limited Sized Patient Cohort for Pre-Operative Risk Stratification in Adult Spinal Deformity Surgery. *J Clin Med* 2024;13. DOI: 10.3390/jcm13030656
38. Jain D, Durand W, Burch S, et al. Machine Learning for Predictive Modeling of 90-day Readmission, Major Medical Complication, and Discharge to a Facility in Patients Undergoing Long Segment Posterior Lumbar Spine Fusion. *Spine (Phila Pa 1976)* 2020;45:1151-60. DOI: 10.1097/BRS.0000000000003475
39. Arora A, Demb J, Cummins DD, et al. Development and internal validation of predictive models to assess risk of post-acute care facility discharge in adults undergoing multi-level instrumented fusions for lumbar degenerative pathology and spinal deformity. *Spine Deform* 2023;11:163-73. DOI: 10.1007/s43390-022-00582-w
40. Lee CH, Jo DJ, Oh JK, et al. Development and Validation of an Online Calculator to Predict Proximal Junctional Kyphosis After Adult Spinal Deformity Surgery Using Machine Learning. *Neurospine* 2023;20:1272-80. DOI: 10.14245/ns.2342434.217
41. Noh SH, Lee HS, Park GE, et al. Predicting Mechanical Complications After Adult Spinal Deformity Operation Using a Machine Learning Based on Modified Global Alignment and Proportion Scoring With Body Mass Index and Bone Mineral Density. *Neurospine* 2023;20:265-74. DOI: 10.14245/ns.2244854.427

42. Balaban B, Yilgor C, Yucekul A, et al. Building clinically actionable models for predicting mechanical complications in postoperatively well-aligned adult spinal deformity patients using XGBoost algorithm. *Informat Med Unlocked* 2023;37:101191. DOI: 10.1016/j.imu.2023.101191
43. Lovecchio F, Lafage R, Sheikh Alshabab B, et al. Can Discharge Radiographs Predict Junctional Complications? A Decision Tree Analysis. *Global Spine J* 2024;14:970-7. DOI: 10.1177/21925682221131765
44. Ryu SJ, So JY, Ha Y, et al. Risk factors for unplanned reoperation after corrective surgery for adult spinal deformity. *Bone Joint Res* 2023;12:245-55. DOI: 10.1302/2046-3758.124.BJR-2022-0121.R1
45. Ames CP, Smith JS, Gum JL, et al. Utilization of Predictive Modeling to Determine Episode of Care Costs and to Accurately Identify Catastrophic Cost Nonwarranty Outlier Patients in Adult Spinal Deformity Surgery: A Step Toward Bundled Payments and Risk Sharing. *Spine* 2020;45
46. Wondra JP, 2nd, Kelly MP, Greenberg J, et al. Validation of Adult Spinal Deformity Surgical Outcome Prediction Tools in Adult Symptomatic Lumbar Scoliosis. *Spine (Phila Pa 1976)* 2023;48:21-8. DOI: 10.1097/BRS.0000000000004416
47. Yagi M, Yamanouchi K, Fujita N, et al. Revolutionizing Spinal Care: Current Applications and Future Directions of Artificial Intelligence and Machine Learning. *J Clin Med* 2023;12. DOI: 10.3390/jcm12134188
48. Haddad S, Pizones J, Raganato R, et al. Future Data Points to Implement in Adult Spinal Deformity Assessment for Artificial Intelligence Modeling Prediction: The Importance of the Biological Dimension. *International Journal of Spine Surgery* 2023;17:S34-S44. DOI: 10.14444/8502
49. Choy W, Azad TD, Scheer JK, et al. Biomarkers in adult spinal deformity surgery. *Seminars in Spine Surgery* 2023;35:101058. DOI: 10.1016/j.semss.2023.101058
50. Galbusera F, Cina A, Samartzis D. Commentary on "Predicting Mechanical Complications After Adult Spinal Deformity Operation Using a Machine Learning Based on Modified Global Alignment and Proportion Scoring With Body Mass Index and Bone Mineral Density". *Neurospine* 2023;20:275-7. DOI: 10.14245/ns.2346296.148