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COMPLICATIONS IN SPINE SURGERY (E KLINEBERG, SECTION EDITOR)

Predictive modeling of complications

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Abstract Predictive analytic algorithms are designed to identify patterns in the data that allow for accurate predictions without the need for a hypothesis. Therefore, predictive modeling can provide detailed and patient-specific information that can be readily applied when discussing the risks of surgery with a patient. There are few studies using predictive modeling techniques in the adult spine surgery literature. These types of studies represent the beginning of the use of predictive analytics in spine surgery outcomes. We will discuss the advancements in the field of spine surgery with respect to predictive analytics, the controversies surrounding the technique, and the future directions.

Keywords Predictive modeling · Predictive analytics · Logistic regression · Adult spinal deformity · Surgical complications

Introduction

The surgical management of adult spinal deformity (ASD) can provide significant improvements in disability, quality of life, and pain [1–5]. However, these operations are technically demanding and can be associated with high rates of complications [6–9]. As the field of spinal deformity surgery has continued to make progress, it has also become more common for surgeons to operate on increasingly challenging cases [10]. The older population has a higher incidence of spinal deformity, and the patient population suitable for these complicated surgeries continues to include patients of advancing age [10, 11]. As the field and surgeons are developing an understanding of the patient-specific limitations to surgery, there has been an interest in predicting which patients will do well following surgery at the initial operative planning stage, prior to the operation.

Patients and surgeons are equally interested in good outcomes, but the reported complication rates in the literature for adult spinal deformity are quite varied and have a large range from 14 to 71 % [6–9]. In some studies, it has been shown that complication rates are higher for patients of older age, three-column osteotomies, and revision surgery [9, 12–14]. Predicting which patient will encounter a complication or even identifying which patient has the highest likelihood of a complication is challenging, and the use of traditional statistics has not been clinically helpful in making these predictions. Traditional statistics is hypothesis driven and relies on many assumptions that often are not easily generalizable. Along with the advent of predictive modeling and predictive analytic techniques, there has been progress in our ability to better predict outcomes without having to succumb to statistical hypotheses, limiting assumptions, nor fitting a complex problem into a single question [15].

More recently, the application of predictive analytics has allowed for the development of accurate, patient-specific, predictive models that can aid in clinical decision-making [16•]. Although traditional statistical methods, including regression analysis, provide insight into which patient characteristics may carry varying levels of risk, these methods are limited

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for use in developing patient-specific predictive models [17]. For example, they generally use patient group means, not accounting for individual changes, or they produce odds and/or hazard ratios for each variable that need to be applied to every patient in a given sample. Moreover, there are many assumptions that need to be satisfied in order to apply regressions and they are generally designed to test specific hypotheses. Conversely, predictive analytic algorithms are designed to identify patterns in the data that allow for accurate predictions without the need for a hypothesis. Therefore, predictive modeling can provide detailed and patient-specific information that can be readily applied when discussing the risks of surgery with a patient.

Predictive models using logistic regression

There are currently only a few predictive models reported in the spine literature. For the ones that do exist, most utilize logistic regression in order to develop a set of odds ratios for developing the outcome of interest [18, 19, 20•, 21, 22]. Logistic regression is commonly used in prediction analysis, and a probabilistic model can be developed to predict adverse outcomes. The outputs of logistic regressions are relative risk values and confidence intervals, which are challenging for patients and physicians to interpret. If the goal of prediction analyses were to facilitate the surgeon and patient in decision-making while taking into account potential complications, then translating this nomenclature to gross probability may be better for patients to understand.

Tetreault and colleagues were the first to evaluate predictors of surgical outcome using linear regression in symptomatic patients with cervical spondylotic myelopathy [22]. Their study findings showed that greater severity scores, smoking, older age, psychological comorbidities, longer duration of symptoms, smaller transverse spinal cord area, and impaired gait presence were associated with a decreased probability of successful outcomes. One of the strengths of the study that is used is a prospectively acquired cohort of 272 patients that included multiple centers [22]. The limitations of the study included a 20 % loss to follow-up at 1 year [22]. Also, all the results were in odds ratios, which prevented the ease and ability to translate this information effectively into a practical, point-of-care setting. Typical patients are a spectrum of all of the variables presented in this manuscript, and it is simply too difficult to make this useful in the clinical setting.

Chapman and colleagues were the first to create a predictive model that examined the risk of medical complications following a spine surgery [20•]. Their model incorporated demographic data, comorbidities, surgical invasiveness, and several other variables from a prospective spine registry. The result was a gross probability output that was easy for patients to understand. This probability score is something that can be better translated into practice, as compared to odds ratios. This study introduced the concept of predicting outcomes as a tool for preoperative patient counseling, shared surgical decision-making, improving safety in spine surgery, and overall for risk stratification [20•].

There are limitations to this study methodology, and limitations that accompany the use of logistic regression for probability prediction. The limitations that are specific to the study include that the accuracy of the model is entirely based on the 1476 patients used to develop the model, without any validated testing of the model [20•]. Also, the study is a complication prediction tool for spine surgery, but it only looks at medical complications, and it does not evaluate surgical complications. Limitations that are specific to the methodology of logistic regression include (a) the number of assumptions that must be satisfied in order to apply logistic regression, (b) for large datasets the *p* values become less meaningful because significance may be achieved solely on the basis of large numbers (i.e., very small difference in means may be statistically significant but not clinically relevant), and (c) they generally provide information on which variables are “predictors” and do not provide a patient-specific interpretation. Advanced modern predictive analytics can now provide accurate and patient-specific predictive models that go beyond the traditional compilation of odds ratios for large groups of patients.

Predictive analytics in spine

Predictive analytics in spine surgery outcomes is a new and emerging field [23]. Predictive analytic algorithms are designed to identify patterns in the data that allow for accurate predictions of a target variable/outcome of interest without the need for a hypothesis. Therefore, predictive modeling can provide detailed and patient-specific information that can be readily applied when discussing the risks of surgery with a patient. There are only a few studies using predictive modeling techniques [16•, 24]. As datasets get larger with time and the quality of the data increases, advanced predictive analytics will likely play a larger role in clinical decision-making.

Spratt and colleagues used the Chi-square Automatic Interaction Detection (CHAID) decision tree analysis to predict successful outcome following decompression for lumbar stenosis. Their model correctly classified 90.1 % of successful outcomes with a positive predictive value 85.7 % and a negative predictive value 100 % [24]. However, their sample size was only 32 patients and they constructed only one decision tree. These types of studies are the beginning of more predictive analytics in spine surgery outcomes. As shown in this study, predictive analytics can be used to identify which patients are the most likely to have a successful surgery.

Daubs and colleagues performed a decision tree analysis and used an ensemble of 50 decision trees in order to evaluate predictors of psychological distress in patients presenting for evaluation of a spinal disorder [16•]. The method of developing a predictive model used in this work was unique in that a model was developed using advanced modern predictive modeling techniques, such as using an ensemble of 50 decision trees to enhance the model predictability. Their model was 92 % accurate, 92 % sensitive, and 95 % specific in predicting a patient's level of psychological distress using 6 variables for 188 patients [16•]. This study validated a very important factor in spine surgery, which is psychological distress. This information can facilitate comprehensive care for a spine patient and provide early identification of potential influences that could impact recovery.

Azimi and colleagues created an artificial neural network predicting 2-year surgical satisfaction in patients with lumbar spinal canal stenosis undergoing surgery and compared the model to traditional logistic regression [25]. They included 168 patients and found the use of artificial neural network to be more accurate than logistic regression. This study identifies yet another method and tool for predicting outcomes that has shown promise in advancing the field. Unique to this study was the incorporation of predicting patient satisfaction as an outcome, which is critically important when patients themselves evaluate their outcome. A limitation of this study included the inability to include all variables that could affect surgical satisfaction. This study was novel in the methodology used and in the outcome variable chosen.

Scheer and colleagues developed a predictive model using an ensemble of decision trees with the outcome being surgical complications [26•]. The target variable used was binary and included patients (1) that sustained at least one major intra- or peri-operative complication or (0) not having any major intra- or peri-operative complications. The decision tree algorithm used five different bootstrapped models [17]. Internal validation was accomplished via a 70:30 data split for training and testing the model, respectively [17]. Final overall predictions from the models were combined and chosen by voting with random selection for tied votes. Overall accuracy and the area under a receiver operator characteristic curve (AUC) were calculated as well as predictor importance as determined by the model. A total of 557 operative patients were available and included in the study. Of those, 409 did not sustain a major complication (NOCOMP, 73.5 %) and 148 had at least 1 intraoperative or peri-operative major complication (COMP, 26.5 %). The overall model accuracy was 87.6 % correct with an AUC of 0.89 indicating a very good model fit [26•].

The predictive model that the Scheer et al. study constructed adheres to several established techniques [26•]. First, decision trees were used, which have many desirable properties including (a) ease of construction, (b) the ability to incorporate both continuous and categorical variables, (c) the capacity to handle hundreds of variables, and (d) feasibility even with missing data [17]. Second, an ensemble of five decision tree models was constructed in which the final predictions were based on the combined predictions from each of the five trees. This is beneficial because the accuracy of the model greatly increases; however, the trade-off is a decrease in interpretability (transparency) [17]. The computer calculates all of the predictions, and thus the exact rules governing how the predictions are made are unavailable. Third, a 70:30 data split was used for training and testing, respectively, in order to increase the generalizability of the model. The 70 % of patients used for training were randomly chosen and were used initially to create the models. Following the construction of the trained model, the remaining 30 % of the patients were "run" through the models in order to predict whether the patients would have a major complication based on the predictions generated from the initial 70 % of the patients. The new predictions from the testing dataset were then compared to what actually happened in the data to produce the accuracy and AUC values. And lastly, for each step of the training and testing stages of the model development, and for each of the five decision trees, the data was bootstrapped meaning a random sample of the data was used each time. Therefore, no model received the same set of patient data for training and for testing, which greatly increases the generalizability of the final model. This study was patient-specific and applied directly to adult spinal deformity patients [26•].

Future directions

The recent introduction and application of predictive modeling in the spine literature is exciting and caries the potential to positively impact surgeons and patients in the future. It is foreseeable that surgical decision-making will involve a predictive analytic model that is designed to take patient characteristics at the point of care and in real-time generate the probabilities of complications for various operative treatment options. At the point of care, this information is patient specific and can influence what surgery is best suited for an individual patient; it may even provide a better discussion for shared decision-making.

In the preoperative setting, a predictive model tool could provide several useful applications. For the surgeon, patient selection is often based on the expected success outcome of surgery. Having an understanding of the risk of complications will have a direct relationship to the success of the surgery and whether the benefit of surgery outweighs the risks involved. Prior to surgery, the surgeon may identify risk factors that could be used to optimize a surgical plan that will result in a complication rate that is low and acceptable to both the surgeon and patient.

Predictive modeling could be further used at the time of surgery to determine the extent of an operation that may be best suited for an individual patient. Adult spinal deformity surgery could be offered in many different ways, and factors that could vary include staged versus a single operation, the extent of the surgery (upper and lower instrumented levels), and whether or not to offer an osteotomy for correction (pedicle subtraction osteotomy versus interbody fusion).

In adult spinal deformity surgery, and spine surgery as a whole, one of the primary goals is to maintain patient safety and minimize complications. How can predictive modeling of complications impact surgeries and make them safer? We foresee the use of predictive modeling as a tool to assist providers to offer surgeries that are the most likely to succeed. It could also provide further input for deciding how extensive an operation a patient should undergo. In situations where the complication probability is high, the surgeon could offer specific complication prevention strategies. Complication prevention strategies could be utilized in the preoperative setting (bone quality improvement strategies), weight loss, operative technique that can include cement augmentation, and posterior tension band preservation or reconstruction.

A predictive analytic model sets the framework to create an application for calculating the risk of developing short-term major complications in real-time as a point-of-care device. In this context, when formulating the surgical plan, and in discussion with the patient, alterations could be made to optimize the risk-benefit equation. For example, a particular surgical technique that may be appropriate in one patient with an otherwise low risk profile may be deemed to be too dangerous in a different patient with a high-predicted baseline risk. Quantifying surgical risk in a given patient represents a significant challenge given the multitude of factors that interact in a complex manner to contribute to the overall risk. Predictive analytic models could be readily applied to this task and yield objective and accurate information to aid surgeons and inform patients.

Conclusion

Despite the abundance of literature describing complication rates and the types of complications in spinal deformity surgery, only recently are models being developed to predict which patients may develop complications following adult spinal deformity [6, 7]. This chapter discusses the advent of a tool that could provide this information, and this may have a beneficial impact on surgeons and patients.

Complication avoidance has been managed in many operative fields by determining the presumed causes and adjusting the surgical plan to minimize these complications. As the field of spinal deformity surgery has continued to progress, it has become more common for surgeons to perform increasingly difficult surgery, operate on an older population, and revise operations that have failed. Even within these circumstances, there will be many patients that will do well and those that may encounter a major complication. This chapter discusses a promising tool that could eventually help navigate decision-making for these challenging cases and have a significant impact on the field of adult spinal deformity.

Compliance with ethical standards

Conflict of interest Joseph A. Osorio and Justin K. Scheer declare that they have no conflict of interest.

Christopher P. Ames reports consultancy fees from Stryker, Medtronic, and DePuy. He also reports royalties from Biomet Spine and Stryker, as well as employment with UCSF, outside of the submitted work. Dr. Ames has a patent issued with Fish & Richardson, P.C.

Human and animal rights and informed consent This article does not contain any studies with human or animal subjects performed by any of the authors.

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