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ORIGINAL ARTICLE

Development of predictive models for all individual questions of SRS-22R after adult spinal deformity surgery: a step toward individualized medicine

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Abstract

Purpose Health-related quality of life (HRQL) instruments are essential in value-driven health care, but patients often have more specific, personal priorities when seeking surgical care. The Scoliosis Research Society-22R (SRS-22R), an HRQL instrument for spinal deformity, provides summary scores spanning several health domains, but these may be difficult for patients to utilize in planning their specific care goals. Our objective was to create preoperative predictive models for responses to individual SRS-22R questions at 1 and 2 years after adult spinal deformity (ASD) surgery to facilitate precision surgical care.

Methods Two prospective observational cohorts were queried for ASD patients with SRS-22R data at baseline and 1 and 2 years after surgery. In total, 150 covariates were used in training machine learning models, including demographics, surgical data and perioperative complications. Validation was accomplished via an 80%/20% data split for training and testing, respectively. Goodness of fit was measured using area under receiver operating characteristic (AUROC) curves.

Results In total, 561 patients met inclusion criteria. The AUROC ranged from 56.5 to 86.9%, reflecting successful fits for most questions. SRS-22R questions regarding pain, disability and social and labor function were the most accurately predicted. Models were less sensitive to questions regarding general satisfaction, depression/anxiety and appearance.

Conclusions To the best of our knowledge, this is the first study to explicitly model the prediction of individual answers to the SRS-22R questionnaire at 1 and 2 years after deformity surgery. The ability to predict individual question responses may prove useful in preoperative counseling in the age of individualized medicine.

IRB approval obtained through each of the member sites contributing cases.

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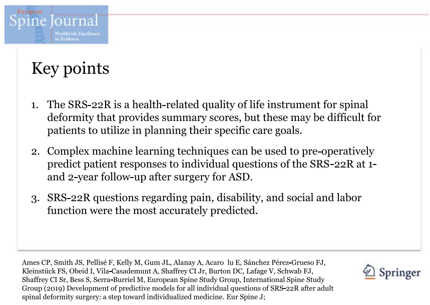
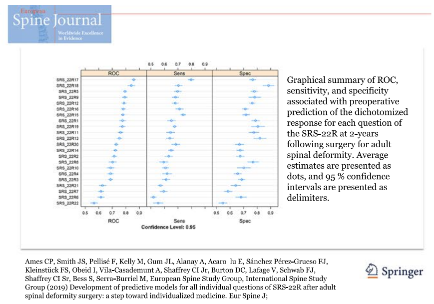
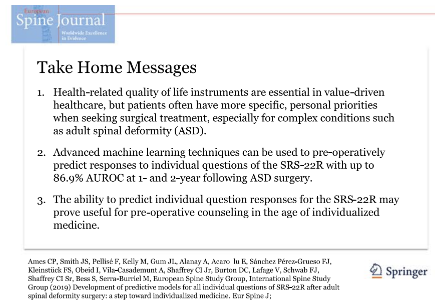
Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.







Keywords Adult spinal deformity · Individualized medicine · Outcomes · Predictive analytics · Scoliosis Research Society-22R (SRS-22R) questionnaire · Surgery

Introduction

Although the finding of adult spinal deformity (ASD) may be incidental or associated with limited symptoms, for many others it may result in substantial pain and disability [1, 2]. Optimal management for symptomatic ASD patients, especially those who have failed non-operative treatments, should be individualized. Several reports suggest that, on average, operative treatment for selected patients with ASD provides relief of pain and disability [3–8]. These findings may be broadly helpful for patient counseling, but they do not address outcomes at the individual patient level, which can range markedly [9]. In addition, surgery for ASD is often complex and associated with high rates of complications [7, 10]. Thus, the decision of whether to pursue operative treatment for the individual ASD patient is often complex and based on an assessment of the potential risks and benefits [7].

The benefits of ASD surgery may be objectively quantified using a variety of patient-reported outcome measures (PROMs), including the Scoliosis Research Society-22R (SRS-22R), Oswestry Disability Index (ODI), Short Form 36 (SF-36) and EuroQol 5D (EQ5-D). These measures are valuable for researchers interested in studying clinical outcomes and for conversion to quality-adjusted life years for the assessment of cost-effectiveness, but they are of limited help to patients. ASD patients contemplating the important decision of whether to pursue surgery often have specific qualitative expectations that cannot be meaningfully addressed based on summary scores from standardized PROMs [11].

The SRS-22R, one of the most widely accepted PROMs for spinal deformity, was initially developed to assess health-related quality of life (HRQL) for patients with adolescent idiopathic scoliosis, but has since been adapted for application to patients with ASD [12, 13]. The SRS-22R provides summary scores based on the patient's responses to 22 questions that each addresses specific areas of potential disease impact (Table 1) [12]. The ability to predict how the disease impact on each of these specific areas may change with surgical treatment for the individual patient could prove invaluable for preoperative counseling.

As the availability of healthcare data is rapidly increasing and tools for big data analysis are advancing, powerful machine learning and computer modeling techniques have been applied to reveal clinically useful information buried within vast amounts of data, as a means of augmenting clinical decision making [14]. Such analyses have been extensively applied across multiple basic science and health fields but have had only limited application to spine research.

The objective of the present study was to develop and test an ensemble of predictive models that can predict the answer to each of the 22 questions from the SRS-22R 1 and 2 years following surgery. In order to do so, advanced modeling techniques were applied to a large series of operatively treated ASD patients. Each model was performed separately with the baseline being set as the preoperative time point or as the postoperative time point in order to assess the potential additive predictive value of early perioperative data. These models may prove useful for more meaningful patient counseling and preoperative decision making while serving as a step toward individualized medicine.

Methods

Study hypothesis

Our hypothesis was that advanced modeling techniques can be used preoperatively and postoperatively to predict

Table 1 Questions and answer options for the Scoliosis Research Society-22R (SRS-22R) questionnaire

#	Question	Answer options
1	Which of the following best describes the amount of pain you have experienced during the past 6 months?	None; mild; moderate; moderate to severe; severe
2	Which one of the following best describes the amount of pain you have experienced over the last month?	None; mild; moderate; moderate to severe; severe
3	During the past 6 months, have you been a very nervous person?	None of the time; a little of the time; some of the time; most of the time; all of the time
4	If you had to spend the rest of your life with your back as it is right now, how would you feel about it?	Very happy; somewhat happy; neither happy nor unhappy; somewhat unhappy; very unhappy
5	What is your current level of activity?	Bedridden; primarily no activity; light labor, such as household chores; moderate manual labor and moderate sports, such as walking and biking; full activities without restriction
6	How do you look in clothes?	Very good; good; fair; bad; very bad
7	In the past 6 months, have you felt so down in the dumps that nothing could cheer you up?	Very often; often; sometimes; rarely; never
8	Do you experience back pain when at rest?	Very often; often; sometimes; rarely; never
9	What is your current level of work/school activity?	100% normal, 75% normal, 50% normal, 25% normal, 0% normal
10	Which of the following best describes the appearance of your trunk, defined as the human body except for the head and extremities?	Very good; good; fair; poor; very poor
11	Which one of the following best describes your medication usage for your back?	None; non-narcotics weekly or less (e.g., aspirin, Tylenol, ibuprofen); non-narcotics daily; narcotics daily; other: medication ______ usage_______ (weekly or less or daily)
12	Does your back limit your ability to do things around the house?	Never; rarely; sometimes; often; very often
13	Have you felt calm and peaceful during the last 6 months?	All of the time; most of the time; some of the time; a little of the time; none of the time
14	Do you feel that your condition affects your personal relationships?	None; slightly; mildly; moderately; severely
15	Are you and/or your family experiencing financial difficulties because of your back?	Severely; moderately; mildly; slightly; none
16	In the past 6 months, have you felt down hearted and blue?	Never; rarely; sometimes; often; very often
17	In the past 3 months, have you taken any sick days from work/school due to back pain and, if so, how many?	0, 1, 2, 3, 4 or more
18	Does your back condition limit your going out with friends/family?	Never; rarely; sometimes; often; very often
19	Do you feel attractive with your current back condition?	Yes, very; Yes, somewhat; neither attractive nor unattractive; no, not very much; no not at all
20	Have you been a happy person during the past 6 months?	None of the time; a little of the time; some of the time; most of the time; all of the time
21	Are you satisfied with the results of your back management?	Very satisfied; satisfied; neither satisfied nor dissatisfied; unsatisfied; very unsatisfied
22	Would you have the same management again if you had the same condition?	Definitely yes; probably yes; not sure; probably not; definitely not

Redrawn from the work of Asher et al. [12]

the answers to each of the 22 questions from the SRS-22R questionnaire at 1 year and 2 years following surgery for ASD.

Patient population

Two independent and compatible prospective multicenter ASD databases, one from the USA and the other from Europe, were queried and merged. Database inclusion criteria were: patients with radiographically confirmed ASD, age ≥ 18 years and planned for surgical treatment. ASD was defined as the presence of at least one of the following: scoliosis ≥ 20°, sagittal vertical axis (SVA) ≥ 5 cm, pelvic tilt (PT) ≥ 25° or thoracic kyphosis (TK) ≥ 60°. In addition, for the present study, patients who were not yet eligible for 2-year follow-up or who lacked SRS-22R data at baseline, 1 year or 2 years were excluded from analysis. Patients were enrolled through an institutional review board-approved protocol at 17 sites (11 in the USA, 2 in Spain, 2 in Turkey, 1 in France and 1 in Switzerland).

Enrollment began September 16, 2008, in the USA and July 27, 2009, in Europe.

Data collection, radiographic assessment and PROMs

Demographic measures included age, sex, height, weight, work status and history of spine surgery. Comorbidities and findings from neurological assessment were extracted from standardized forms completed at baseline. Full-length free-standing antero-posterior and lateral spine radiographs were analyzed using validated software [15–17] for the assessment of radiographic parameters based on standard techniques [18]. PROMs included the SRS-22R, ODI and SF36v2, which were completed at preoperative baseline and at 1 and 2 years following surgery.

Collected surgical characteristics included: operative time, estimated blood loss (EBL), number of fused vertebral levels, use of pelvic fixation, use of interbody fusion (IBF), whether an osteotomy was performed and type, and length of hospital stay (LOS). Perioperative major complications (prior to hospital discharge) were assessed as recommended by Carreon et al. [19].

Model predictors and outcomes

In total, 150 variables were used for model training, including demographics, comorbidities, modifiable surgical variables, radiographic parameters, hospital and surgeon. For each SRS-22R question, the five potential responses range from best to worst and were dichotomized into two groups, with the bottom three responses grouped as "bad" and the top two responses grouped as "good." Five-class classification of each individual answer to each question was also conducted as a check of robustness.

Statistical analysis

All numeric predictors were normalized, and non-variant predictors were dropped. Six different prediction algorithms with feature selection or automated variable inclusion were trained at four time horizons for each of the 22 outcomes. The six prediction algorithms were: elastic net [20], gradient boosting machines [21], extreme gradient boosting tree [22], extreme gradient boosting linear [22], random forest [23] and elastic net regularized generalized linear models [24]. The advantage of such algorithms over more traditional methods such as logistic regression appears on three features: (1) the lack assumptions regarding the association of predictors and outcomes (standard methods require few collinear variables), (2) an automated procedure to detect significant interactions between predictors (interaction have to be specified before the training) and (3) embed dimensionality reduction (algorithms suited to large p, small n cases). The six chosen algorithms represent variations of two major families: regularized regression and ensemble algorithms.

The four time horizons were: (1) baseline to 1 year only using data available at the preoperative time point (pre-op baseline to 1 year); (2) baseline to 1 year using data available up to the time of discharge from the hospital following surgery (post-op baseline to 1 year); (3) baseline to 2 years only using data available at the preoperative time point (pre-op baseline to 2 years); (4) baseline to 2 years using data available up to the time of discharge from the hospital following surgery (post-op baseline to 2 years). Examples of information available for the post-op, but not for the pre-op, time horizons include EBL, LOS and occurrence of perioperative complications. The surgical plan was considered known at the preoperative time point. Within baseline time horizons, preoperative models were fitted.

External validation was accomplished via an 80%/20% data split for model training and testing, respectively, with a fivefold cross-validation in the training sample to avoid overfitting. Missing values were imputed with random forest multiple imputation [25] with an out-of-bag (OOB) error rate of 0.06. Class unbalance was solved by means of upscaling the training sets [26]. Goodness of fit was measured as area under the receiver operating characteristic (AUROC) values in the test set, with their 95% CI. Model selection for each time prediction interval was based on AUROC maximization. A 0.05 level of statistical significance was used across all analyses. The probability of improvement was based on raw class probabilities prediction. For five-class classification, accuracy and kappa metrics were used as goodness-of-fit metrics. All analyses were performed in R 3.4.3 [27]. A TRIPOD [28] complete checklist is provided as supplementary material (Supplementary Table 1).

Results

Of 1612 patients, 1064 (66.0%) were eligible for 2-year follow-up. Of those eligible for 2-year follow-up, 869 (81.7%) achieved 2-year follow-up, and of these patients, 561 (64.6%) met inclusion criteria and had sufficiently complete data at baseline and follow-up. Table 2 presents descriptive statistics for assessed patient parameters. The mean patient age was 54.4 years, and women represented 75.9% of the patients. Almost one-half of patients (44.6%) had a history of spine surgery (Table 2). Baseline comorbidities and neurological status are summarized in Tables 3 and 4, respectively.

Table 2 Patient parameters: demographics, radiographic measures and patient-reported outcome scores for 561 adult spinal deformity patients

Variable	Mean or %	SD	Median	SE
Preoperative baseline				
Age (years)	54.4	17.0	58.2	0.7
Sex (% women)	75.9			
Height (cm)	163.6	9.8	163.5	0.4
Weight (kg)	71.6	17.3	68.5	0.7
Work status (%)				
Employed	55.4			
Employed and student	1.1			
Retired due to age	20.7			
Retired due to back pain (permanent)	4.7			
Sick leave (temporary)	5.7			
Student	3.2			
Unemployed	9.2			
Smoker (%)	10.3			
Previous spine surgery (%)	44.6			
Sagittal alignment (SVA, mm)	52.6	71.6	41.8	3.1
Coronal alignment (GCA, mm)	31.6	31.8	23.8	1.4
Major curve Cobb angle (°)	42.2	21.4	41.1	0.9
Pelvic tilt (°)	22.3	11.1	22	0.5
Oswestry Disability Index	40.3	19.3	40	0.8
SRS-22R function score	3.08	0.91	3	0.04
SRS-22R mental health score	3.4	0.9	3.4	0.04
SRS-22R pain score	2.55	0.91	2.4	0.04
SRS-22R self-image score	2.49	0.74	2.4	0.03
SRS-22R subtotal score	2.88	0.67	2.91	0.03
SF36v2 MCS score	45.3	13.4	46.3	0.58
SF36v2 PCS score	33.89	10.22	32.91	0.44
1 Year postoperative				
Sagittal alignment (SVA, cm)	22.06	54.4	16	2.4
Coronal alignment (GCA, cm)	3.96	31.4	6.5	1.4
Major curve Cobb angle (°)	8.82	25.76	10.9	1.2
Pelvic tilt (°)	20.5	9.7	20.6	0.4
Oswestry Disability Index	24.9	17.9	22	0.8
SRS-22R function score	3.61	0.88	3.6	0.04
SRS-22R mental health score	3.86	0.83	4.00	0.04
SRS-22R pain score	3.55	0.97	3.60	0.04
SRS-22R self-image score	3.71	0.83	3.80	0.04
SRS-22R subtotal score	3.74	0.71	3.83	0.03
SF36v2 MCS score	50.5	11.7	53.9	0.5
SF36v2 PCS score	42.1	9.9	42.6	0.4
2 Years postoperative				
Sagittal alignment (SVA, mm)	26.3	54.1	22.7	2.4
Coronal alignment (GCA, mm)	23.77	20.16	18.74	0.9
Major curve Cobb angle (°)	21.21	16.11	17.9	0.72
Pelvic tilt (°)	20.25	10.08	20.07	0.45
Oswestry Disability Index	25.4	19.4	22	0.8
SRS-22R function score	3.62	0.94	3.8	0.04
SRS-22R mental health score	3.83	0.85	4.00	0.04
SRS-22R pain score	3.52	1.06	3.6	0.04
SRS-22R self-image score	3.66	0.87	3.8	0.04
SRS-22R subtotal score	3.7	0.77	3.8	0.03
SF36v2 MCS score	49.81	11.98	51.09	0.5
SF36v2 PCS score	41.34	10.98	41.95	0.5

SD standard deviation, *SE* standard error, *SVA C7-S1 sagittal vertical axis*, *GCA* global coronal alignment, *SRS* Scoliosis Research Society, *MCS* Mental Component Score, *PCS* Physical Component Score

Surgical parameters are presented in Table 5. Mean surgical time was 368 min, and mean EBL was 1573 cc. On average, patients had 10.5 vertebral levels fused and LOS averaged 8.3 days. For most patients, surgical treatment included pelvic fixation (60.8%), interbody fusion (62.1%) and/or Smith–Petersen osteotomy (49.5%). Perioperative complications were reported in 9.98% of patients. The most common perioperative complications included surgical site infections, neurologic, implant-related and radiographic. A detailed assessment of the complications from the US cohort has been previously published [10].

Mean and median scores for each question of the SRS-22R at baseline and at 1- and 2-year follow-up are shown in Table 6. Dichotomized values (scores 1–3 vs 4–5) for each question of the SRS-22R are summarized in Fig. 1.

Of the six algorithms assessed, the ones with the highest AUROC were selected. Table 7 provides the model

Table 3 Baseline comorbidities for 561 adult spinal deformity patients

Comorbidity	%
Hypertension	26.9
Arthritis	26.2
Depression	17.7
Osteoporosis	9.3
Heart disease	8.9
Cancer	8.7
Anemia	8.0
Ulcer and/or stomach disease	7.8
Diabetes	6.1
Lung disease	5.9
Psychiatric disorder (other than depression)	3.9
Blood clots	3.0
Nervous system disorder	2.7
Kidney disease	2.0
Peripheral vascular disease	1.8
Alcohol/drug abuse	1.6
Liver disease	0.9

Table 4 Baseline neurological status for 561 adult spinal deformity patients

Neurological parameter	%
Bladder incontinence	13.2
Bowel incontinence	5.8
Leg weakness	43.5
Loss of balance	33.5
Numbness/tingling in legs	45.4
Gait unsteadiness	6.8
Inability to heel walk	7.6
Inability to toe walk	5.8

selection by question and time horizon. Figure 2 provides a graphical summary of the AUROC, sensitivity and specificity associated with prediction of dichotomized responses for each question of the SRS-22R based on the assessed time horizons: baseline to 1 year and baseline to 2 years, with each performed using pre-op and post-op baselines. A total of 88 out of 528 models were selected.

The AUROC of the models varied depending upon the question (Fig. 2). For the pre-op baseline to 1-year time horizon, question 17 was predicted with an AUROC of 82.5% (95% CI 80.6–84.4%), while question 21 had an AUROC of only 58.1% (95% CI 56.1–60%) (Fig. 2a, upper panel). The post-op baseline to 1-year time horizon had similar results, with question 17 again having the highest AUROC (86.9%, 95% CI 85.8–89.7%) and question 21 having the lowest AUROC (59.3%, 95% CI 57–61.5%) (Fig. 2a, lower panel). For the baseline to 2-year models, question 17 was best predicted, with AUROCs of 85.2% (95% CI 84.6–87.1%) and 86.2% (95% CI 84.5–87.8%) for the pre-op and post-op baseline time horizons, respectively (Fig. 2b, upper and lower panels, respectively). The poorest predicted question was number 22, with AUROCs of 56.5% (95% CI 54.1–59%) and 59.6% (95% CI 56.9–62.2%) for the pre-op and post-op baseline time horizons, respectively (Fig. 2b, upper and lower panels, respectively).

These results highlight the low incremental predictive power that post-op baseline models have with the addition of relevant information not known preoperatively. The difference across best/worst models is approximately 27 out of 50 possible percental AUROC points, indicating a difference in performance of approximately 43%.

The AUROC of most models was greater than 70%, indicating a successful fit out of sample (Fig. 2). Responses to SRS-22R questions 1, 5, 9, 12, 15, 17 and 18 of the SRS-22R were among those predicted with the best AUROC regardless of the time horizon. Responses to questions 3, 4, 6, 7, 8, 21 and 22 were among those predicted with consistently lower AUROC.

Five-class classification of each individual answer to each question of the SRS-22R produced predictive accuracy ranging from approximately 35–80% and kappa estimates ranging from 20 to 75% depending on the question (Supplementary Figure 1). The accuracy of each model was statistically greater than the no information rate.

Discussion

Through the application of advanced machine learning techniques, the present study has demonstrated that it is possible to predict some responses to the individual questions of the SRS-22R outcome instrument up to an 86.9% AUROC at 1 and 2 years following surgical treatment for ASD. The main clinical application of the present study is to aid surgical decision-making processes. Informed decision making requires patient comprehension of expected outcomes of surgery. Moving away from average outcomes or even stratified predictions into personalized outcome prediction is expected to enhance the well-being of patients. Imagine a case where a patient's goal is to recover a previous activity level where she/he could perform light physical activities. The explicit

Table 5 Surgical parameters for 561 adult spinal deformity patients

Variable	Mean or %	SD	Median	SE
Total surgical time (min)	368.4	132.7	364.0	7.7
Estimated blood loss (cc)	1572.5	1491.6	1200.0	85.8
Number of fused vertebral levels	10.5	4.3	10.0	0.3
Use of pelvic fixation (%)	60.8			
Use of interbody fusion (%)	62.1			
Use of Smith–Petersen osteotomy (%)	49.5			
Use of pedicle subtraction osteotomy (%)	14.6			
Use of vertebral column resection (%)	4.2			
Length of hospitalization (days)	8.25	5.84	7.0	0.2
Occurrence of perioperative complication (%)	9.98			

SD standard deviation, *SE* standard error

Table 6 SRS-22R scores for each question for 561 adult spinal deformity patients at baseline and 1 and 2 years following surgery

Question number	Time point	Mean	SD	Median	SE
1	Baseline	2.47	1.07	2	0.04
	1 year	3.25	1.02	3	0.04
	2 years	3.25	1.10	3	0.05
2	Baseline	2.58	1.13	2	0.05
	1 year	3.40	1.05	4	0.04
	2 years	3.32	1.14	3	0.05
3	Baseline	3.67	1.06	4	0.04
	1 year	3.98	1.00	4	0.04
	2 years	3.95	0.98	4	0.04
4	Baseline	2.17	1.26	2	0.05
	1 year	3.40	1.34	4	0.06
	2 years	3.41	1.32	4	0.06
5	Baseline	3.39	1.03	3	0.04
	1 year	3.72	0.93	4	0.04
	2 years	3.72	0.97	4	0.04
6	Baseline	3.31	0.92	3	0.04
	1 year	3.71	0.87	4	0.04
	2 years	3.64	0.87	4	0.04
7	Baseline	3.87	1.11	4	0.05
	1 year	4.15	0.99	4	0.04
	2 years	4.14	1.03	4	0.04
8	Baseline	2.88	1.16	3	0.05
	1 year	3.51	1.09	4	0.05
	2 years	3.48	1.10	3	0.05
9	Baseline	3.59	1.40	4	0.06
	1 year	3.88	1.24	4	0.05
	2 years	3.82	1.29	4	0.05
10	Baseline	2.74	1.01	3	0.04
	1 year	3.44	1.01	3	0.04
	2 years	3.36	1.02	3	0.04
11	Baseline	3.15	1.49	3	0.06
	1 year	3.47	1.44	4	0.06
	2 years	3.50	1.45	4	0.06
12	Baseline	2.79	1.24	3	0.05
	1 year	3.31	1.10	3	0.05
	2 years	3.28	1.16	3	0.05
13	Baseline	3.40	0.93	4	0.04
	1 year	3.68	0.89	4	0.04
	2 years	3.65	0.91	4	0.04
14	Baseline	3.39	1.36	4	0.06
	1 year	3.91	1.23	4	0.05
	2 years	3.87	1.25	4	0.05
15	Baseline	4.37	1.08	5	0.05
	1 year	4.45	1.05	5	0.04
	2 years	4.51	1.02	5	0.04
16	Baseline	3.58	1.11	4	0.05
	1 year	3.89	1.01	4	0.04
	2 years	3.88	1.05	4	0.04
17	Baseline	3.67	1.72	5	0.07
	1 year	4.14	1.47	5	0.06
	2 years	4.11	1.49	5	0.06
18	Baseline	3.35	1.31	3	0.06
	1 year	3.70	1.21	4	0.05
	2 years	3.74	1.19	4	0.05
19	Baseline	2.83	1.09	3	0.05
	1 year	3.40	1.06	3	0.04
	2 years	3.35	1.08	3	0.05
20	Baseline	3.58	0.88	4	0.04
	1 year	3.84	0.83	4	0.04
	2 years	3.82	0.83	4	0.03
21	Baseline	2.99	1.18	3	0.05
	1 year	3.94	1.04	4	0.04
	2 years	3.88	1.05	4	0.04
22	Baseline	3.43	1.17	3	0.05
	1 year	4.24	0.98	5	0.04
	2 years	4.18	1.01	4	0.04

SD standard deviation, *SE* standard error

individualized probability of that happening after surgery should play a central role in the decision to undergo surgery.

The two main time points with respect to the surgery, pre-op and post-op, have differential clinical applications. The pre-op models could be used in routine practice to inform shared decision making regarding the decision to undergo surgery, while post-op models could be used to allocate resources and to update expectations.

Multiple time horizons were also assessed in the present study: baseline to 1 year and baseline to 2 years, with each performed using data available at the pre-op and post-op baseline time points. Regardless of time horizon, it is notable that most of the best and worst predicted questions were similar. Responses to SRS-22R questions 1, 5, 9, 12, 15, 17 and 18 were among those predicted with the best AUROC. Question 1 specifically assesses pain within the last 6 months. Questions 5 and 12 reflect current level of activity in general and level of domestic activity, respectively. Current level of work/school activity and days of sick leave from work are assessed through questions 9 and 17, respectively. Financial difficulties, which may relate to the ability to work, are captured through question 15. Social activity, specifically the ability to go out with family and friends, is assessed through question 18. Collectively, these questions with the greatest predictive sensitivity specifically address many of the primary issues that commonly motivate ASD patients to seek treatment, including pain, disability, and social and labor function.

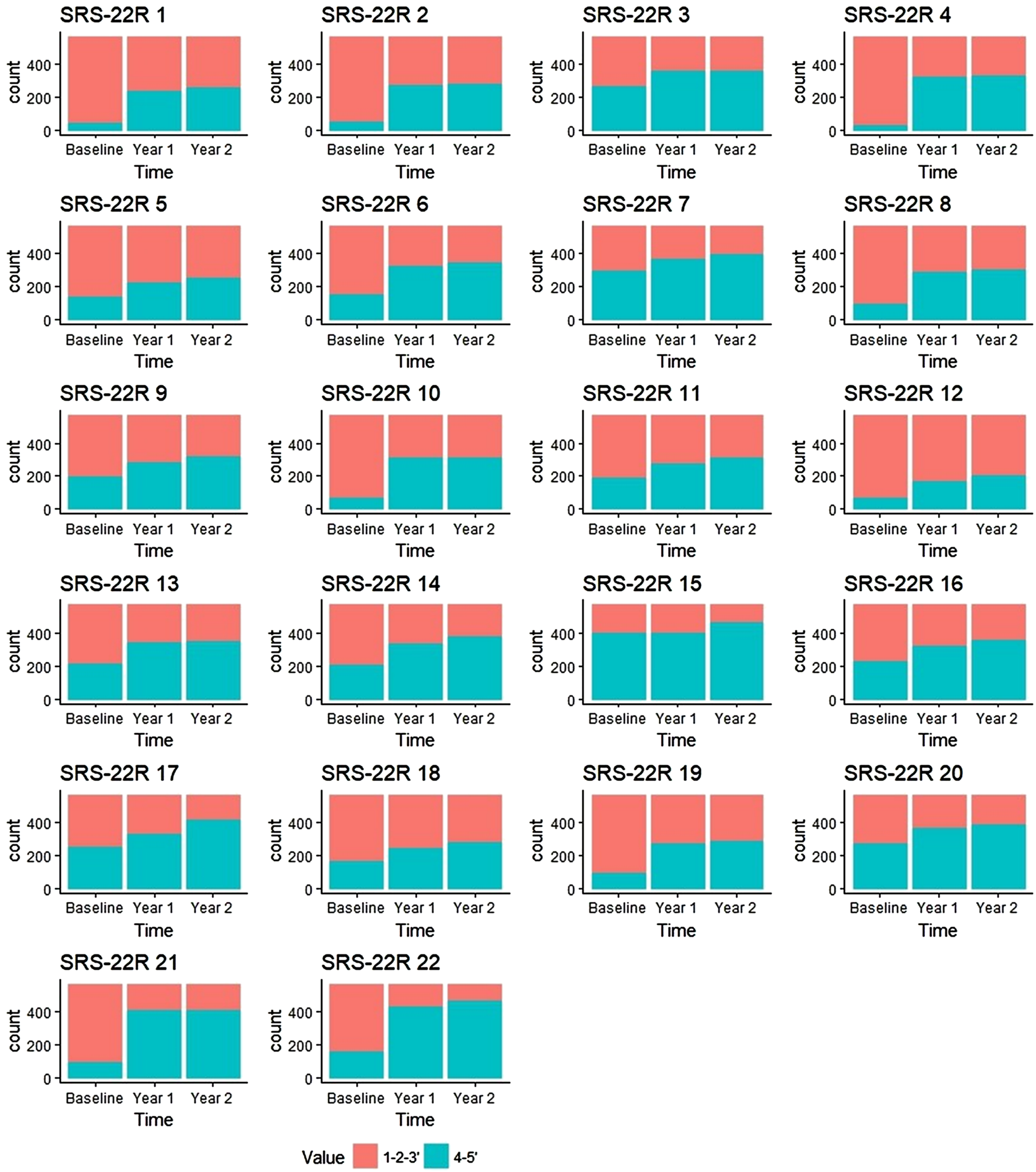


Fig. 1 Summary of dichotomized responses to each question of the SRS-22R from 561 adult spinal deformity patients at baseline and 1- and 2-year postoperative time points. For each of the SRS-22R questions, the five potential responses range from worst to best and were dichotomized into one of the two groups, with the bottom three responses grouped as "bad" and the top two responses grouped as "good"

SRS-22R questions 3, 4, 6, 7, 8, 21 and 22 were among those predicted with the lowest AUROC. Question 6 relates to appearance. Questions 7 and 3 assess symptoms of depression and anxiety, respectively. Questions 4, 21 and 22 reflect general satisfaction and whether the patient would choose the same path if he or she had to start again. Back

Table 7 Selected models by question and time horizon

	Bl–1 year pre-op	Bl–1 year post-op	Bl–2 years pre-op	Bl–2 years post-op
SRS-22R 1	GBM	GBM	GBM	GBM
SRS-22R 2	GLMnet	GLMnet	GLMnet	GLMnet
SRS-22R 3	GBM	GBM	ELnet	ELnet
SRS-22R 4	RF	RF	RF	RF
SRS-22R 5	GBM	GBM	GLMnet	GLMnet
SRS-22R 6	XGBT	XGBL	XGBT	XGBL
SRS-22R 7	GBM	GBM	XGBT	XGBT
SRS-22R 8	RF	RF	RF	RF
SRS-22R 9	GBM	GBM	GLMnet	GLMnet
SRS-22R 10	GLMnet	GLMnet	XGBT	XGBT
SRS-22R 11	GBM	GBM	ELnet	ELnet
SRS-22R 12	ELnet	ELnet	RF	RF
SRS-22R 13	XGBT	XGBT	GLMnet	GLMnet
SRS-22R 14	XGBL	XGBL	RF	RF
SRS-22R 15	GBM	GBM	RF	RF
SRS-22R 16	GBM	GBM	RF	RF
SRS-22R 17	GBM	GBM	XGBT	XGBT
SRS-22R 18	XGBL	XGBL	GBM	GBM
SRS-22R 19	ELnet	ELnet	XGBL	XGBL
SRS-22R 20	ELnet	ELnet	RF	RF
SRS-22R 21	GBM	GBM	XGBT	XGBT
SRS-22R 22	RF	RF	GBM	GBM

Bl baseline, *GBM* gradient boosting machine, *GLMnet* elastic net regularized generalized linear model, *ELnet* elastic net regularization, *RF* random forest, *XGBL* extreme gradient boosting linear, *XGBT* extreme gradient boosting tree

pain at rest is assessed by question 8. It is perhaps not surprising that predicting satisfaction with treatment is harder than more objective measures, especially due to the low incidence of dissatisfied patients. It is notable that prediction of symptoms of depression and anxiety had a relatively low sensitivity, which may be affected by a mix of patients with situational clinical depression and anxiety that may be difficult to distinguish. The fact that question 1 relates to pain and is one of the best predicted answers, while question 8 relates to pain at rest and is one of the worst predicted highlights the differential nature of specific questions regarding predictability.

Several recent reports have described the application of predictive analytics to the surgical treatment of ASD [29–32]. For example, Scheer and colleagues have provided ASD surgery models to predict the occurrence of major complications with 87% accuracy, to predict the occurrence of clinically significant proximal junctional kyphosis with 86% accuracy and to predict the likelihood of achieving a minimal clinically important difference for ODI [29–31]. These models and others provide tools to address specific questions that may be useful for preoperative patient counseling. The present study extends beyond these previous reports by providing patients with predictions of their outcomes based on questions that were specifically designed to be easy to understand and to focus on the most relevant issues impacted by their disease.

Primary strengths of the current analyses include use of data from multiple centers across the USA and Europe, which enhances the generalizability of the findings. In addition, the depth of data granularity is substantially greater than is available through most data registries. The present study is not without limitations. Although 561 ASD patients represent a relatively large number, data-intensive machine learning techniques benefit from even larger populations. We acknowledge as well that self-reported answers to questions are susceptible to cognitive bias [33]. We also note that current iterations of these models are limited in their ability to predict discrete responses to SRS-22R questions, rather than the dichotomized outcomes. This, however, is unlikely to be a limitation from the perspective of patient counseling as we generally aim to communicate whether results will be "good" or bad." We also acknowledge that the described predictive models are not static and are likely to undergo further iterative refinements as future data are accumulated.

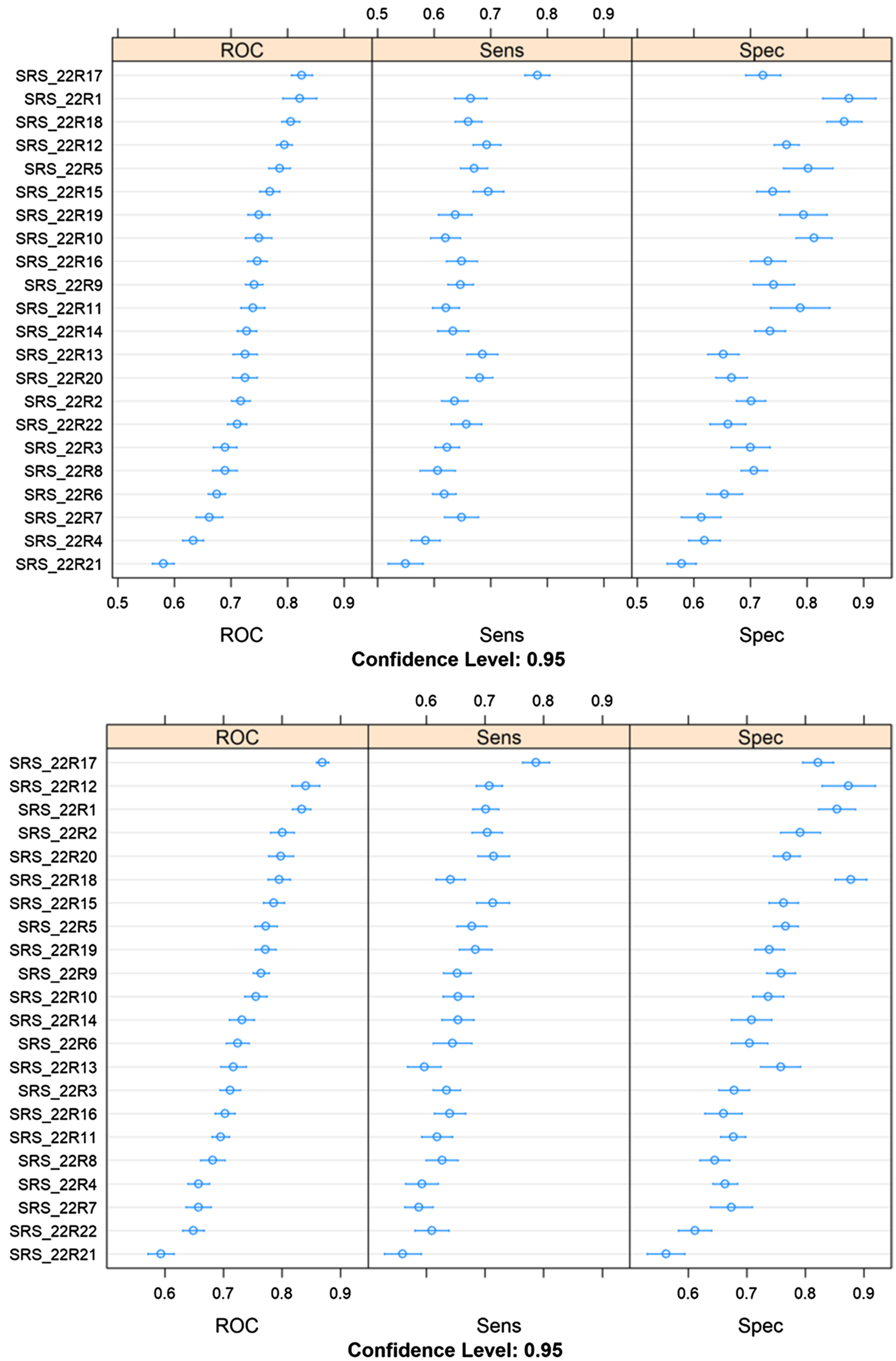
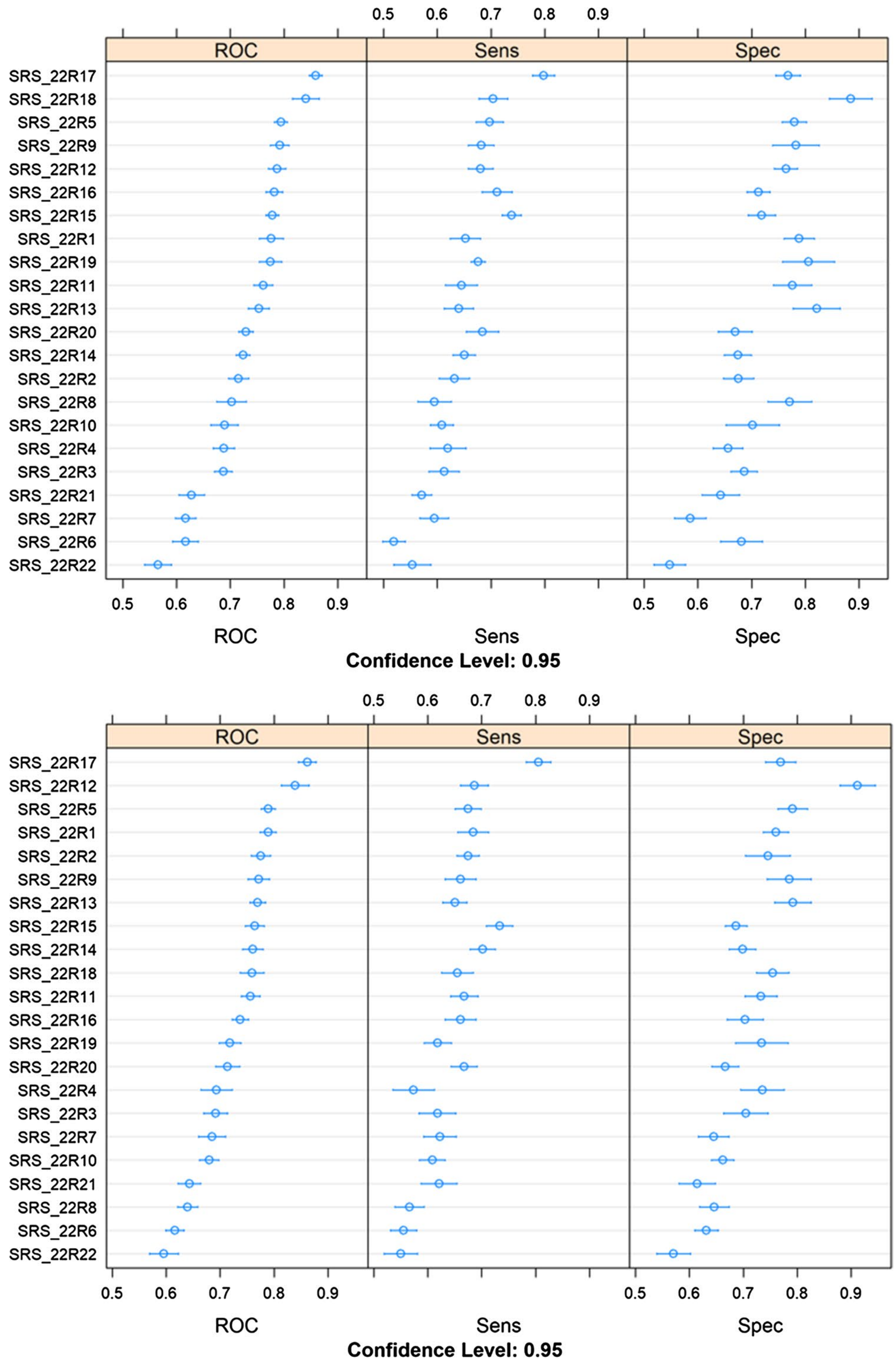


Fig. 2 Graphical summary of the ROC, sensitivity and specificity associated with prediction of the dichotomized response for each question of the SRS-22R based on two assessed baseline time horizons, preoperatively and postoperatively: **a** baseline to 1 year and **b** baseline to 2 years. The upper panels represent the preoperative baseline models (i.e., models only include information available prior to surgery), and the lower panels represent the postoperative baseline models (i.e., models include information available up to the point of hospital discharge following surgery). Average estimates are presented as dots, and 95% confidence intervals are presented as delimiters

Conclusions

Preoperative models to predict answers to each SRS-22R question at 1- and 2-year follow-up were created with up to 86.9% AUROC. Items related to pain, disability and social and labor function were most accurately predicted. The ability to predict individual question responses may prove useful in preoperative counseling in the age of individualized medicine.

Fig. 2 (continued)



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Compliance with ethical standards

Conflict of interest Dr. Ames reports personal fees from DePuy Synthes, personal fees from Stryker, personal fees from Biomet Spine, personal fees from NuVasive, personal fees from Next Orthosurgical, personal fees from DePuy Synthes, personal fees from Medtronic, personal fees from Stryker, personal fees from Medicrea, personal fees from K2M, personal fees from UCSF, outside the submitted work. Dr. Smith reports grants from DePuy Synthes/ISSG, during the conduct of the study; personal fees from Zimmer Biomet, personal fees from NuVasive, personal fees from K2M, personal fees from AlloSource, from Cerapedics, grants from NREF, grants from AOSpine, from DePuy Synthes/ISSG, outside the submitted work. Dr. Pellisé reports grants from DePuy Synthes Spine, grants from Fondo de Investigaciones Sanitarias, during the conduct of the study; personal fees from DePuy Synthes Spine, grants from Medtronic, grants from Zimmer Biomet, outside the submitted work. Dr. Kelly reports grants from AOSpine, grants from DePuy Synthes, grants from DePuy Synthes, outside the submitted work. Dr. Gum reports grants from DePuy Synthes Spine, personal fees from Acuity, personal fees from Alphatec Spine, personal fees from DePuy Synthes, personal fees from K2M, personal fees from Medtronic, personal fees from NuVasive, personal fees from Stryker Spine, outside the submitted work. Dr. Alanay reports grants from DePuy Synthes, during the conduct of the study; grants from DePuy Synthes, grants from outside the submitted work. Dr. Acaroglu reports grants from DePuy Synthes, during the conduct of the study; grants from Medtronic, personal fees from AOSpine, outside the submitted work. Dr. Sánchez Pérez-Grueso reports grants and other from DePuy Synthes, other from K2M, outside the submitted work. Dr. Kleinstueck reports grants from DePuy Synthes, during the conduct of the study. Dr. Obeid reports grants from DePuy Synthes, during the conduct of the study; personal fees from DePuy Synthes, personal fees from Medtronic, personal fees from Alphatecspine, personal fees from Spineart, personal fees from Clariance, outside the submitted work. Dr. Vila-Casademunt has nothing to disclose. Mr. Shaffrey has nothing to disclose. Dr. Burton reports grants, personal fees and other from DePuy Spine, non-financial support from International Spine Study Group, non-financial support from Scoliosis Research Society, non-financial support from University of Kansas Physicians, other from Bioventus, other from Pfizer, outside the submitted work. Dr. Lafage reports grants from SRS, NASS, grants from DePuy Spine, grants from NuVasive, grants from Stryker, grants from K2M, personal fees from DePuy Spine, personal fees from AO Spine, personal fees from K2M, outside the submitted work. Dr. Schwab reports grants from DePuy Spine, grants from Stryker, grants from K2M, grants from NuVasive, personal fees from Medicrea, personal fees from Zimmer Biomet, personal fees from NuVasive, personal fees from K2M, personal fees from MSD, other from Nemaris INC, outside the submitted work. Dr. Shaffrey reports grants from ISSG Foundation, during the conduct of the study; personal fees from Medtronic, personal fees from NuVasive, personal fees from Zimmer Biomet, outside the submitted work. Dr. Bess reports grants from DePuy Synthes Spine, grants from K2 Medical, during the conduct of the study; grants from NuVasive, grants from Medtronic, grants from Stryker Spine, grants from Biomet Spine, grants from Orthofix, personal fees from K2 Medical, outside the submitted work. Dr. Serra-Burriel has nothing to disclose.

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