Title

Unsupervised Clustering of Adult Spinal Deformity Patterns Predicts Surgical and Patient-Reported Outcomes.

Permalink

https://escholarship.org/uc/item/8v34h0s2

Authors

Lafage, Renaud
Song, Junho
Elysee, Jonathan
et al.

Publication Date

DOI

Peer reviewed

Unsupervised Clustering of Adult Spinal Deformity Patterns Predicts Surgical and Patient-Reported Outcomes

Renaud Lafage, MS[1] ⓘ, Junho Song, MD[2], Jonathan Elysee, MS[1],
Mitchell S. Fourman, MD, MPhil[3] ⓘ, Justin S. Smith, MD, PhD[4], Christopher Ames, MD[5],
Shay Bess, MD[6], Alan H. Daniels, MD[7] ⓘ, Munish Gupta, MD[8] ⓘ, Richard Hostin, MD[9],
Han Jo Kim, MD[10] ⓘ, Eric Klineberg, MD[11], Gregory Mundis, MD[12], Bassel G. Diebo, MD[7] ⓘ,
Christopher Shaffrey, MD[13], Frank Schwab, MD[1], Virginie Lafage, PhD[1] ⓘ,
Douglas Burton, MD[14], and on behalf of International Spine Study Group

Abstract

Study Design: Retrospective cohort study.

Objectives: To evaluate whether different radiographic clusters of adult spinal deformity identified using artificial intelligence-based clustering are associated with distinct surgical outcomes.

Methods: Patients were classified based on the results of a previously conducted analysis that examined clusters of deformity, including Moderate Sagittal (Mod Sag), Severe Sagittal (Sev Sag), Coronal, and Hyper-Thoracic Kyphosis (Hyper-TK). The surgical data, HRQOL, and complication outcomes of these clusters were then compared.

Results: The final analysis included 1062 patients. Similar to published results on a different patient sample, Mod Sag and Sev Sag patients were older, more likely to have a history of previous spine surgery, and more disabled. By 2-year, all clusters improved in HRQOL and reached a similar rate of minimal clinically important difference (MCID).
The Sev Sag cluster had the highest rate major complications (53% vs 34-40%), and complications leading to reoperation (29% vs 17-23%), implant failures (20% vs 8-11%), and operative complications (27% vs 10-17%). Coronal patients had the highest rate of pulmonary complications (9% vs 3-6%) but the lowest rate of X-ray imbalance (10% vs 19-21%). No significant differences were

[1] Department of Orthopedic Surgery, Northwell Health, Lenox Hill Hospital, New York, NY, USA

[2] Icahn School of Medicine at Mount Sinai, New York, NY, USA

[3] Department of Orthopaedic Surgery, Montefiore Medical Center, Bronx, NY, USA

[4] Department of Neurosurgery, University of Virginia Medical Center, Charlottesville, VA, USA

[5] Department of Neurosurgery, University of California School of Medicine, San Francisco, CA, USA

[6] Denver International Spine Center, Presbyterian St. Luke's/Rocky Mountain Hospital for Children, Denver, CO, USA

[7] Department of Orthopedic Surgery, Brown University, Providence, RI, USA

[8] Department of Orthopedic Surgery, Washington University, St. Louis, MO, USA

[9] Department of Orthopaedic Surgery, Southwest Scoliosis Institute, Dallas, TX, USA

[10] Department of Orthopedic Surgery, Hospital for Special Surgery, New York, NY, USA

[11] Department of Orthopedic Surgery, UTHealth, Hoston, TX, USA

[12] Department of Orthopedic Surgery, Scripps Clinic Torrey Pines, La Jolla, CA, USA

[13] Department of Neurosurgery, Duke University Medical Center, Durham, NC, USA

[14] Department of Orthopedic Surgery, University of Kansas Medical Center, Kansas City, KS, USA

Corresponding Author:
Renaud Lafage, MS, Department of Orthopaedic Surgery, Northwell Health, Lenox Hill Hospital, 130 East 77th Street, 12th Floor, New York, NY 10075, USA.
Email: renaud.lafage@gmail.com

found in neurological complications, infection rate, gastrointestinal, or cardiac events (all $P > .1$). Kaplan-Meier survival curves demonstrated a lower time to first complications for the Sev Sag cluster.

Conclusions: All clusters of adult spinal deformity benefit similarly from surgery as they all achieved similar rates of MCID. Although the rates of complications varied among the clusters, the types of complications were not significantly different.

Keywords

adult spinal deformity, artificial intelligence, clustering, machine learning, minimum clinically important difference, patient-reported outcomes, sagittal alignment, sagittal balance, scoliosis, surgical outcomes

Introduction

Adult spinal deformity (ASD) affects as many as 60% of the elderly population and often leads to detrimental effects on function and quality of life.[1-3] Bess et al demonstrated that ASD affects the patient's quality of life to the same degree as other debilitating chronic diseases such as diabetes, heart disease, and rheumatoid arthritis.[4] Surgical deformity correction is often indicated to provide improvement in quality of life in patients with reduced disability; however, careful consideration of patient and deformity characteristics is paramount in surgical decision-making at the individual patient level.[5]

Classification systems of ASD driven by artificial intelligence (AI) algorithms have the potential to provide valuable patient-focused data to help guide surgical decision-making and patient counseling.[6,7] Kim et al. used a two-step cluster analysis to determine 3 distinct clusters of cervical deformity.[8] Using unsupervised hierarchical clustering, Ames et al. identified twelve subgroups of ASD patients based on radiographic, surgical, and patient factors to aid with preoperative decision-making.[9] Finally, Lafage et al applied an unsupervised AI approach to a large multicenter database of complex ASD patients and identified 4 natural clusters of deformity, including Hyper-Thoracic Kyphosis (Hyper-TK), Moderate Sagittal (Mod Sag), Severe Sagittal (Sev Sag), and Coronal.[10] Moreover, these deformity cohorts were associated with distinct perioperative outcomes.

These studies highlight the extensive clinical and radiographic heterogeneity of ASD and warrant a more thorough evaluation of the differences in surgical and patient-reported outcomes across deformity clusters. Therefore, the current study applied the previously established AI-based clustering techniques[10] on a separate database of surgical ASD patients and compared the treatment outcomes associated with various deformity clusters. We hypothesized that distinct clusters of deformity would be associated with differences in 2-year postoperative HRQOL outcomes after ASD surgery.

Methods

Patient Population

We conducted a retrospective analysis of a prospective multicenter database of ASD patients. Institutional review board (IRB) approval was obtained at each site prior to study initiation, and informed consent was obtained from each patient. We included patients above 18 years of age who met the radiological criteria of ASD (coronal Cobb angle >20°, sagittal vertical axis [SVA] >5 cm, pelvic tilt [PT] >25°, or TK >60°) and underwent ASD surgery. Exclusion criteria included trauma, active tumor, inflammatory conditions, and neuromuscular disorders. Details can be find on Clinical-Trials.gov website, under ID NCT00738439.

Data Collection

Prospective data were collected via IRB-approved proprietary study group clinical research forms that included demographic data (age, sex, race, body mass index [BMI]) and past medical history (Charlson Comorbidity Index [CCI], prior spine surgery, American Society of Anesthesiologists [ASA] score). Collected surgical details included locations of the posterior instrumentation upper-most instrumented vertebra (UIV) and lower-most instrumented vertebra (LIV), utilization of interbody fusion (IBF), direct decompression, osteotomy, and 3-column osteotomy (3CO). Perioperative data including length of hospital stay (LOS), intensive care unit (ICU) stay, and estimated blood loss (EBL) were also recorded.

Standardized patient-reported outcomes (health-related quality of life [HRQOL]) were collected preoperatively and 2 years postoperatively and included numeric rating scale (NRS) for back and leg pain, Oswestry Disability Index (ODI), 36-Item Short Form Survey (SF-36), and Scoliosis Research Society 22-Item Scale (SRS-22). Achievement of minimal clinically important difference (MCID) was analyzed, which was defined as a change pre- to post-operatively greater than 15 points for ODI, 5.2 points for SF-36, .374 points for SRS Activity, .586 points for SRS Pain, and .790 points for SRS Appearance. Complications within the 2-year postoperative period were recorded and stratified based on severity (major vs minor adverse event, requirement of reoperation) and type (medical vs surgical).

Full-length free-standing anterior-posterior and lateral spine radiographs were obtained pre- and postoperatively and were analyzed by 2 trained independent observers using a dedicated software (Spineview, ENSAM Laboratory of Biomechanics, Paris, France).[11] Radiographic parameters were extracted and calculated using Matlab (MathWork, Natick, Massachusetts).

Table 1. Value of Centroid of Previously Published Clusters of Deformity.

	PI-LL	T2-T12	TPA	Thoracic Cobb	Lumbar Cobb
Mod sag	20.0	−40.1	26.4	7.6	20.0
Hyper-TK	−25.7	−82.6	3.6	20.0	38.7
Coronal	16.1	−32.2	21.3	42.3	58.0
Sev sag	52.6	−29.8	48.6	12.0	20.0

Radiographic parameters collected included pelvic tilt (PT), pelvic incidence (PI), lumbar lordosis (LL), spinopelvic mismatch between PI and LL (PI-LL), T1 pelvic angle (TPA), sagittal vertical axis (SVA), and thoracic and thoracolumbar Cobb angles. Patients were also classified according to the SRS-Schwab Classification.[12]

Deformity Clusters

Unsupervised cluster analysis was used to classify patients based on their coronal and sagittal deformity into 1 of 4 deformity clusters: Hyper-Thoracic Kyphosis (Hyper-TK), Moderate Sagittal (Mod Sag), Severe Sagittal (Sev Sag), and Coronal. Clustering was performed using a TwoStep (SPSS) cluster analysis, which is an exploratory tool that can detect naturally occurring groups within a dataset. A k-means cluster analysis was performed using mean values of the previously published analysis as the initial centroid for the different clusters[10] (Table 1, Figure 1).

Statistical Analysis

Descriptive statistics were provided for all demographic, clinical, and radiographic data using mean ± standard deviation (StD), median and interquartile range (IQR), or frequencies, as appropriate. Deformity cluster cohorts were compared based on preoperative information, perioperative variables, and 2-year postoperative outcomes (pre- to postoperative changes in HRQOLs, rate of MCID achievement, and complication rates) using Kruskal-Wallis, analysis of variance (ANOVA), or Chi-Square test, as appropriate. After stratification by deformity type, multivariate logistic regression controlling for age, BMI, CCI, ASA, and preoperative HRQOL was conducted to evaluate whether surgical procedure was independently associated with MCID achievement or complication. All statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY). The level of statistical significance was set at $P < .05$ a priori.

Results

Cohort Description

There was a total of 1476 eligible patients in the database, out of which 1062 patients (72%) completed their 2-year postoperative follow-up and were included in the study. The median follow-up period was 25 months (IQR 24 to 30 months). The study cohort had a mean age of 60.6 ± 14.2 years, mean BMI of 28.1 ± 5.9 kg/m^2, 809 (76.2%) female patients, and 935 (88.0%) white patients. Median CCI was 1.5 (IQR 0 to 3), 528 (49.7%) patients with ASA grade 2, and 432 (40.7%) patients with ASA grade 3. Preoperative HRQOLs revealed moderate to severe baseline disability and pain, with a median NRS back pain of 8 (IQR 6 to 9) and 59.5% of patients with ODI >40. In assessment of preoperative SRS Classification, there were 431 (40.6%) patients classified with a curve type of N, 339 (31.9%) classified with L, and 249 (23.4%) classified with D. 682 (64.2%) patients had a PI-LL modifier of "+" or "++," 708 (66.7%) patients had a PT modifier of "+" or "++," and 636 (59.9%) patients had an SVA modifier of "+" or "++."

Posterior fixation was performed in 99.0% of patients included in the analysis. Median number of levels treated was 9 (IQR 8 to 14), 59.8% of patients had between 5 to 12 levels treated, and 29.1% had 13 or more levels treated. Direct decompression was performed in 59.0% of the cases. Some osteotomy was performed in 70.9% of cases, while major osteotomy (pedicle subtraction osteotomy [PSO] or vertebral column resection [VCR]) was performed in 17.4% of cases. 65.0% of cases involved interbody fusion techniques. Supplemental rod was used in 19.5% of cases, while bone morphogenetic protein (BMP) was used in 68.0% of cases.

The median EBL was 1300 cc (IQR 600 to 2150). 64.9% of patients required ICU stay postoperatively, and 13.7% required longer than 48 h of ICU stay. The median LOS was 7 days (IQR 5 to 9).

Type of Deformity

The results of k-means classification are demonstrated in Table 2. 371 (34.9%) patients had Mod Sag deformity, 210 (19.8%) patients had Sev Sag deformity, 177 (16.7%) patients had Hyper-TK deformity, and 304 (28.6%) patients had severe Coronal deformity. By design, there were significant differences in preoperative alignment among these 4 clusters (all $P < .001$). Significant differences in demographic and clinical characteristics among clusters were noted. Hyper-TK and Coronal patients tended to be younger, healthier, with fewer revision cases compared to Mod Sag and Sev Sag patients. There were no differences in follow-up rates among the clusters. In terms of baseline HRQOL scores, Coronal patients presented with less back pain than other deformity types. Coronal and Hyper-TK clusters had less leg pain than Mod Sag and Sev Sag types. Coronal and Hyper-TK clusters also had lower disability and better physical score compared to Mod Sag and Sev Sag clusters.

2-Year Postoperative Outcomes

Comparison of 2-year postoperative HRQOL outcomes demonstrated significant differences among the different
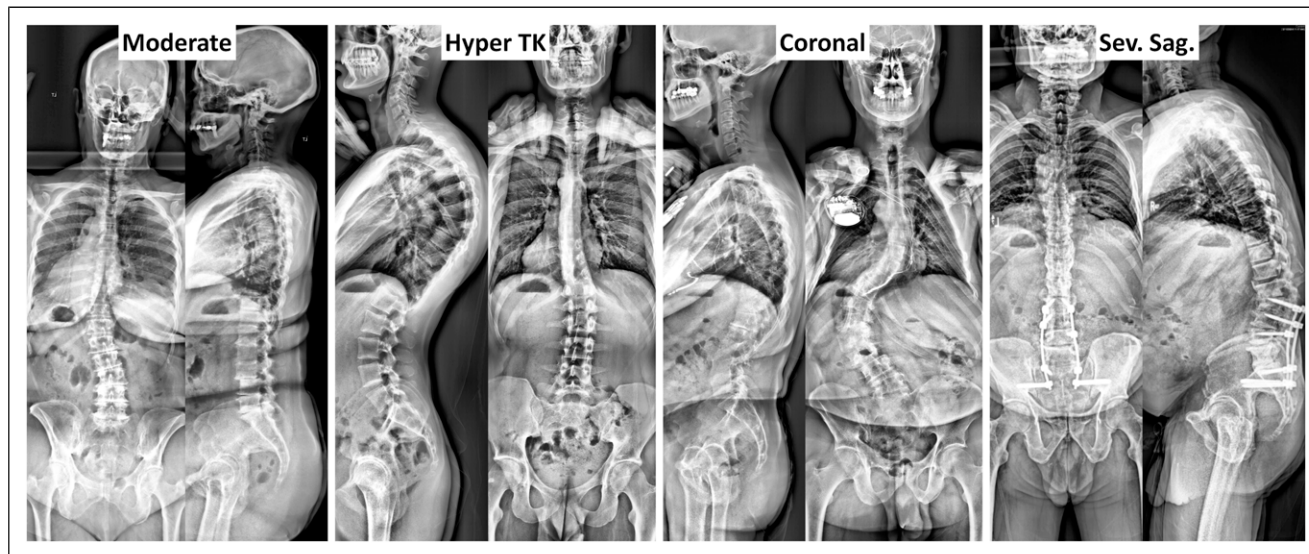
Figure 1. Examples of type of deformity from previously published cluster of deformity.

Table 2. Results of the Classification Using K-Mean, Including Radiographic Alignment (PI-LL, TK, TPA, TH. Scoli and Lumbar Scoli), Demographic Information (Age, Charlson Comorbidity Index [CCI], Follow-Up [FU] and Prior Surgery) and Patient Reported Outcomes [PRO] (Numerical Rating Scale [NRS] Back and Leg Pain, Oswestry Disability Index [ODI], SF36 Physical Component Score [PCS] and Mental Component Score [MCS], SRS-22 Domains and Total Score).

		Moderate	Hyper TK	Coronal	Sev. Sag	P-Value
X-ray	PI-LL (°)	17.7 +/− 9	−9.4 +/− 12.2	11.7 +/− 16.4	44.4 +/− 12.3	By design
	TK (°)	−40.7 +/− 13.3	−61.8 +/− 17.5	−33.1 +/− 15.6	−20.5 +/− 14.6	By design
	TPA (°)	24.6 +/− 8.9	11.6 +/− 9.1	19 +/− 11.3	38.4 +/− 11	By design
	Th. Scoli (°)	8.5 +/− 8.4	15.2 +/− 15.1	45 +/− 17.9	12 +/− 12.5	By design
	Lumbar scoli (°)	24.7 +/− 13.7	28.9 +/− 15.7	54.4 +/− 17	25 +/− 15.9	By design
Demo	Age (years)	65.4 +/− 10.4	56.8 +/− 18.3	54 +/− 14.6	65 +/− 10.3	<.001
	CCI	2 (1 to 3)	1 (0 to 3)	1 (0 to 2)	2 (1 to 3)	<.001
	FU (month)	25 (24 to 29)	25 (24 to 31)	25 (24 to 29)	25 (24 to 32)	.552
	Prios sx?	61.60%	38.40%	28.70%	74.80%	<.001
PRO	NRS back	8 (6 to 9)	8 (6.5 to 9)	7 (5 to 8)	8 (6 to 9)	<.001
	NRS leg	6 (3.5 to 8)	4.5 (1 to 7)	3 (0 to 7)	6 (3 to 8)	<.001
	ODI	48.1 +/− 14.9	41 +/− 17.1	36.7 +/− 18.2	52.3 +/− 14.2	<.001
	SF36 PCS	28.7 +/− 7.8	33.2 +/− 1.3	35.3 +/− 1.5	26.9 +/− 7.2	<.001
	SF36 MCS	45 +/− 13.9	45.6 +/− 13.6	47.5 +/− 12.5	43.8 +/− 13.7	.018
	SRS22 activity	2.7 +/− .8	3 +/− .9	3.2 +/− .9	2.5 +/− .7	<.001
	SRS22 pain	2.2 +/− .7	2.5 +/− .8	2.7 +/− .9	2.1 +/− .7	<.001
	SRS22 appearance	2.5 +/− .7	2.5 +/− .8	2.5 +/− .7	2.1 +/− .7	<.001
	SRS22 mental	3.4 +/− .9	3.5 +/− .8	3.6 +/− .9	3.3 +/− .9	.006
	SRS22 total	2.7 +/− .6	2.9 +/− .6	3 +/− .6	2.5 +/− .6	<.001

types of deformity, except for the SF-36 Mental Component Score. Compared to other types, Coronal patients generally had better outcomes, with lower pain scores (NRS back 2 vs 3-4, $P = .009$; NRS leg 0 vs 1-2, $P < .001$), less disability (ODI 21.2 vs 26.1-33.7, $P < .001$), better appearance score (3.9 vs 3.3-3.6, $P < .001$), and higher activity score (3.8 vs 3.2-3.6, $P < .001$). Conversely, Sev Sag patients had higher disability at 2-year follow-up than other clusters (33.7 vs 21.2-30.3, $P < .001$).

There were significant differences in SRS-22 Patient Satisfaction scores at 2-year follow-up between the clusters. Coronal patients demonstrated higher satisfaction (4.3 ± .9) than other types of deformity (Mod Sag: 4.1 ± 1.0; Hyper-TK: 4.1 ± 1.0; Sev Sag: 4.1 ± 1.0, $P < .035$). In response to the question, "Are you satisfied with the results of your back management?" 75.5% of Coronal patients answered either "Satisfied" or "Very satisfied," compared to 64.0% for Sev Sag, 66.4% for Mod Sag, and 72.4% for Hyper-TK ($P = .017$).

Table 3. 2-Year Post-operative Patient-Reported Outcomes Across the Different Clusters of Deformity as Well as Rate of Patient Reaching Minimum Clinically Important Difference [MCID].

	Mod Sag	Hyper-TK	Coronal	Sev Sag	P-Value
NRS back	4 (1 to 7)	4 (1 to 6)	2 (0 to 5)	3 (1 to 7)	.009
NRS leg	2 (0 to 5)	1 (0 to 4)	0 (0 to 4)	2 (0 to 6)	<.001
ODI	30.3 +/− 19.4	26.1 +/− 19.7	21.2 +/− 19	33.7 +/− 21.1	<.001
SF36 PCS	37.3 +/− 10.9	40.4 +/− 11.8	44.1 +/− 11.2	36.1 +/− 10.9	<.001
SF36 MCS	51.2 +/− 12.1	49.8 +/− 12.5	51.7 +/− 11	49.1 +/− 13.3	.169
SRS22 activity	3.4 +/− .9	3.6 +/− 1	3.8 +/− .9	3.2 +/− .9	<.001
SRS22 pain	3.4 +/− 1.1	3.4 +/− 1	3.7 +/− 1	3.3 +/− 1.1	.001
SRS22 appearance	3.4 +/− .9	3.6 +/− 1	3.9 +/− .9	3.3 +/− 1	<.001
SRS22 mental	3.8 +/− .8	3.8 +/− .9	3.9 +/− .8	3.7 +/− .9	.019
SRS22 total	3.6 +/− .8	3.6 +/− .8	3.8 +/− .8	3.4 +/− .8	<.001
MCID ODI?	52.4%	49.4%	51.0%	52.0%	.929
MCID PCS?	61.5%	57.9%	62.3%	60.3%	.820
MCID activity?	69.9%	62.1%	61.7%	67.4%	.113
MCID pain?	73.6%	66.9%	67.6%	72.0%	.254
MCID appearance?	58.0%	65.7%	77.9%	67.2%	<.001

However, there was no statistically significant difference among the deformity types in their responses to the question, "Would you have the same management again if you had the same condition?," with the response rate of either "Probably" or "Definitely" ranging from 77.2% to 84.4% ($P = .103$).

Comparison of MCID achievement rate among deformity types demonstrated a significant difference only for SRS-22 Appearance scores. Coronal patients tended to achieve MCID for SRS-22 Appearance at a higher rate than Mod Sag patients (77.9% vs 58.0%, $P < .001$). Otherwise, no significant differences were noted in MCID achievement rates for ODI, SF-36 PCS, SRS-22 Activity, SRS-22 Pain, and SRS-22 Appearance (all $P > .1$) (Table 3).

Survival curves up to 730 days (2 years) was analyzed and revealed significant differences in survival functions among types of deformity (Figure 2). For any type of complication (log rank $P = .014$, pairwise comparison demonstrated a significant difference between Hyper-TK and other types (all $P < .05$). For any complication outside of adverse events (log rank $P = .001$), Hyper-TK patients had a higher survival rate than other types (all $P < .05$). Sev Sag had a lower survival curve than Coronal ($P = .021$) and a trend toward lower survival curve than Mod Sag, although it was statistically insignificant ($P = .052$). There was no significant difference in survival function between Coronal and Mod Sag. When evaluating survival functions for major complication leading to reoperation (log rank $P = .003$), Sev Sag type demonstrated significantly lower survival function than Coronal ($P < .001$), Mod Sag ($P = .028$), and a trend toward lower than Hyper-TK ($P = .059$). There were no significant differences for major complication not leading to reoperation (log rank $P = .057$), although Sev Sag trended toward having a lower survival function. There were no significant differences in survival functions for medical complications (log rank $P = .061$). For survival rate of surgical complications (log rank $P < .001$), there were significant differences in survival function between Coronal/Hyper-TK vs Mod Sag vs Sev Sag types (all pairwise $P < .05$). However, there was no significant difference between Coronal and Hyper-TK types.

Multilinear analyses were performed within each cluster, controlling for preoperative information. For Mod Sag patients, having more than 12 levels fused increased the likelihood of reaching MCID for ODI (odds ratio [OR] 3.456 [1.389 − 8.596]) and MCID for PCS (OR 3.456 [1.389 − 8.596]), while having 1-4 levels fused decreased the likelihood of having any complication (OR 0.364 [0.182 − 0.730]) and major complications (OR 0.402 [0.196 − 0.827]). In addition, the use of BMP increased the likelihood of complication (OR 1.778 [1.008 − 3.138]), while 3CO increased the likelihood for major complication (OR 3.774 [1.837 − 7.753]) and reoperation (OR 2.520 [1.247 − 5.093]).

Within the Coronal cluster, use of IBF increased the likelihood of reaching MCID for ODI (OR 2.470 [1.311 − 4.656]) and SRS-22 Activity (OR 2.141 [1.105 − 4.150]), but also increased the likelihood of any complication (OR 2.337 [1.249 − 4.375]) and major complication (OR 2.210 [1.167 − 4.185]). The use of supplemental rod increased the likelihood of reaching MCID for ODI (OR 2.057 [1.006 − 4.206]) and SRS-22 Activity (OR 2.281 [1.049 − 4.959]) and decreased the chance of reoperation (OR 0.255 [0.093 − 0.701]). Long constructs increased the likelihood of complication (OR 1.897 [1.013 − 3.553]), major complication (OR 2.878 [1.538 − 5.388]), and reoperation (OR 2.949 [1.371 − 6.346]), while use of osteotomy decreased the likelihood of complications (OR 0.449 [0.218 − 0.925]).

For the Hyper-TK clusters, use of BMP decreased the likelihood of reaching MCID for PCS (OR 0.308 [0.112 − 0.847])
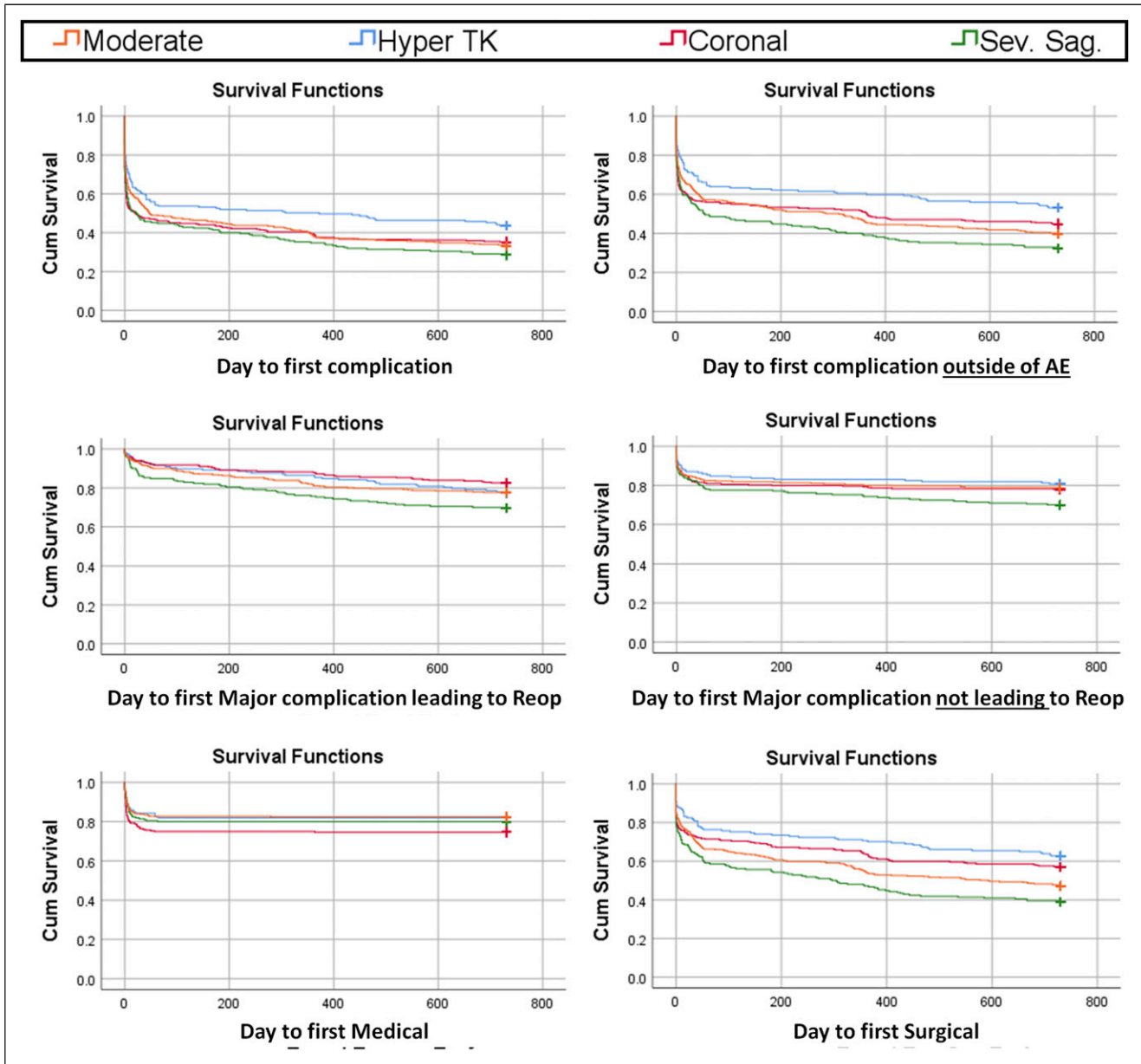
Figure 2. Kaplan-Meier survival curves up to 720 days by type of deformity including survival rate until first complication (top left); survival rate until first complication outside of unrelated AE (top right); survival rate until first major complication requiring a reoperation (middle left); survival rate until first major complication not requiring a reoperation (middle right); survival rate until first medical complication (bottom left); and survival rate until first surgical complication (bottom right).

and the likelihood of having a major complication (OR 0.237 [0.093 – 0.606]). Use of minimally invasive (MIS) techniques for posterior fusion decreased the likelihood of reaching MCID for SRS-22 Appearance (OR 0.246 [0.063 – 0.968]) and having a major complication (OR 0.117 [0.023 – 0.594]). Having a long construct increased the likelihood of having a complication (OR 4.313 [1.433 – 12.98]).

Finally, among Sev Sag patients, having a short construct decreased the likelihood of reaching MCID for SRS-22

Activity (OR 0.052 [0.004 – 0.630]) and Appearance (OR 0.090 [0.008 – 0.967]).

Discussion

Adult spinal deformity has a profound impact on patient quality of life.[4,13] The substantial clinical, radiographic, and operative heterogeneity associated with ASD often makes clinical decision-making and patient counseling

challenging.[14-16] AI-based hierarchical clustering has the promising potential to augment patient-specific care by incorporating numerous variables into granular patient population segmentation.[17-19] In the current study, we employed a previously established unsupervised clustering algorithm to categorize 1062 ASD patients into 4 distinct deformity subgroups and investigated the 2-year postoperative outcomes for each deformity type. While the deformity clusters exhibited differences in baseline and postoperative HRQOLs, the rates of MCID achievement were similar. These findings provide valuable insights into the heterogeneity of ASD patients, emphasizing the importance of understanding distinct clusters of deformity and their implications for surgical outcomes.

The deformity subtypes utilized in this study were described in a previous clustering analysis of a database of 286 complex ASD patients, which showed that radiographic clustering was intimately associated with host characteristics such as demographics and level of disability.[10] Although these 4 clusters are not the only presentations of complex ASD, they serve as a reflection of the significant heterogeneity of the ASD population. In our cohort, the 4 clusters had distinct baseline clinical and radiographic properties, with the Hyper-TK subtype generally being younger and associated with the lowest disability and pain scores preoperatively. Conversely, Mod Sag and Sev Sag cohorts were older, more disabled at baseline, and more likely to have a history of spine surgery. These findings are consistent with the published results on a different dataset and may reflect the fact that thoracic hyperkyphosis in adults often results from long-term progression of a congenital condition, such as Scheuermann's kyphosis, as opposed to a predominantly degenerative disease.[10,20]

All clusters demonstrated significant improvements in HRQOLs postoperatively, achieving MCID at similar rates by 2 years postoperatively. However, the magnitude and trajectory of improvement varied among clusters, with some groups experiencing more pronounced residual disability and pain at the 2-year follow-up. Coronal patients generally had better postoperative outcomes, with lower pain scores, less disability, better appearance score, and higher activity score. In addition, the Coronal cluster had a higher rate of MCID achievement for SRS-22 appearance compared to the Mod Sag cluster. Conversely, Sev Sag patients were most likely to remain disabled postoperatively than other cohorts and demonstrated lower survival function for major complications leading to reoperation. This is consistent with the previously demonstrated linear relationship between the degree of sagittal imbalance and severity of disability in patients with adult spinal deformity.[21,22] Such direct relationship with clinical outcomes has been less consistently reproduced with regard to coronal balance, with several investigations finding that coronal malalignment is not a predictive factor for complications and reoperation after ASD surgery.[23-25]

The current study also evaluated the surgical factors associated with outcomes for each cluster. Within the Mod Sag cluster, fusion involving more than 12 levels increased the likelihood of achieving MCID for ODI and PCS, and 1-4 level fusion was associated with a lower complication risk. Among Coronal patients, the use of a supplemental rod was associated with favorable outcomes, increasing the likelihood of MCID achievement for ODI and activity scores while decreasing the risk of reoperation. Long constructs were associated with higher rates of all complications, major complications, and reoperation. Long constructs were similarly associated with poor outcome in the Hyper-TK cohort, increasing the likelihood of complications. Lastly, within the Sev Sag cluster, short constructs were associated with lower likelihood of achieving MCID for activity and appearance.

Several limitations must be considered when interpreting this study. The retrospective study design limits the level evidence and the conclusions that can be drawn. This radiographic classification is limited to ASD patients who were surgically treated only by members of our study group; inclusion of non-operative patients and patients treated at additional clinical sites may reveal greater diversity of deformity clusters. In addition, this classification does not consider the cervical spine, horizontal gaze acquisition, or lower extremity compensation. Thus, further investigation incorporating full-body image analysis may allow the development of a more detailed classification system. Finally, while our study provides valuable data on 2-year postoperative outcomes, future studies with longer follow-up periods may provide additional insight as some patients may experience loss of alignment and deterioration beyond the 2-year follow-up period.[26,27]

Conclusion

This study applied established AI-based clustering techniques on a database of surgical ASD patients and compared the treatment outcomes associated with various deformity clusters. All clusters of deformity achieved MCID at similar rates, although the Coronal deformity cluster showed significantly higher MCID achievement rate in appearance score. Although the rates of complications varied among the clusters, the types of complications were not significantly different. By elucidating distinct ASD clusters and their clinical implications, the current study may allow for better anticipation of long-term surgical outcomes and underscores the potential utility of machine learning clustering as a prognostic tool in ASD patients.

ORCID iDs

Renaud Lafage https://orcid.org/0000-0002-4820-1835
Mitchell S. Fourman https://orcid.org/0000-0001-5886-546X
Alan H. Daniels https://orcid.org/0000-0001-9597-4139
Munish Gupta https://orcid.org/0000-0002-4711-4377
Han Jo Kim https://orcid.org/0000-0003-2170-3592
Bassel G. Diebo https://orcid.org/0000-0002-7835-2263
Virginie Lafage https://orcid.org/0000-0002-0119-7111

References

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(9):1082-1085. doi:10.1097/01.brs.0000160842.43482.cd

2. Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR. Correlation of radiographic parameters and clinical symptoms in adult scoliosis. *Spine*. 2005;30(6):682-688. doi:10.1097/01.brs.0000155425.04536.f7

3. Glassman SD, Schwab FJ, Bridwell KH, Ondra SL, Berven S, Lenke LG. The selection of operative versus nonoperative treatment in patients with adult scoliosis. *Spine*. 2007;32(1):93-97. doi:10.1097/01.brs.0000251022.18847.77

4. Bess S, Line B, Fu KM, et al. The health impact of symptomatic adult spinal deformity: comparison of deformity types to United States population norms and chronic diseases. *Spine*. 2016;41(3):224-233. doi:10.1097/brs.0000000000001202

5. Moal B, Lafage V, Smith JS, et al. Clinical improvement through surgery for adult spinal deformity: what can Be expected and who is likely to benefit most? *Spine Deform*. 2015;3(6):566-574. doi:10.1016/j.jspd.2015.04.004

6. 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(5):1223-1239. doi:10.1007/s43390-021-00360-0

7. 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. *Internet J Spine Surg*. 2023;17(S1):S34-S44. doi:10.14444/8502

8. Kim HJ, Virk S, Elysee J, et al. The morphology of cervical deformities: a two-step cluster analysis to identify cervical deformity patterns. *J Neurosurg Spine*. 2019;32:353-359. doi:10.3171/2019.9.Spine19730

9. Ames CP, Smith JS, Pellisé F, et al. Artificial intelligence based hierarchical clustering of patient types and intervention categories in adult spinal deformity surgery: towards a new classification scheme that predicts quality and value. *Spine*. 2019;44(13):915-926. doi:10.1097/brs.0000000000002974

10. Lafage R, Fourman MS, Smith JS, et al. Can unsupervised cluster analysis identify patterns of complex adult spinal deformity with distinct perioperative outcomes? *J Neurosurg Spine*. 2023;38(5):1-11. doi:10.3171/2023.1.Spine221095

11. Champain S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. *Eur Spine J*. 2006;15(6):982-991. doi:10.1007/s00586-005-0927-1

12. Schwab F, Ungar B, Blondel B, et al. Scoliosis research society-schwab adult spinal deformity classification: a validation study. *Spine*. 2012;37(12):1077-1082. doi:10.1097/BRS.0b013e31823e15e2

13. Schwab F, Dubey A, Pagala M, Gamez L, Farcy JP. Adult scoliosis: a health assessment analysis by SF-36. *Spine*. 2003;28(6):602-606. doi:10.1097/01.Brs.0000049924.94414.Bb

14. Ames CP, Scheer JK, Lafage V, et al. Adult spinal deformity: epidemiology, health impact, evaluation, and management. *Spine Deform*. 2016;4(4):310-322. doi:10.1016/j.jspd.2015.12.009

15. Smith JS, Shaffrey CI, Fu KM, et al. Clinical and radiographic evaluation of the adult spinal deformity patient. *Neurosurg Clin*. 2013;24(2):143-156. doi:10.1016/j.nec.2012.12.009

16. Lafage R, Song J, Diebo B, et al. Alterations in magnitude and shape of thoracic kyphosis following surgical correction for adult spinal deformity. *Global Spine J* 2023; 21925682231218003. doi:10.1177/21925682231218003

17. Rajkomar A, Dean J, Kohane I. Machine learning in medicine. *N Engl J Med*. 2019;380(14):1347-1358. doi:10.1056/NEJMra1814259

18. 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;24:1095-1108. doi:10.1016/j.spinee.2024.02.010

19. Durand WM, Lafage R, Hamilton DK, et al. Artificial intelligence clustering of adult spinal deformity sagittal plane morphology predicts surgical characteristics, alignment, and outcomes. *Eur Spine J*. 2021;30(8):2157-2166. doi:10.1007/s00586-021-06799-z

20. Horn SR, Poorman GW, Tishelman JC, et al. Trends in treatment of Scheuermann kyphosis: a study of 1,070 cases from 2003 to 2012. *Spine Deform*. 2019;7(1):100-106. doi:10.1016/j.jspd.2018.06.004

21. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. *Spine*. 2005;30(18):2024-2049. doi:10.1097/01.brs.0000179086.30449.96

22. Youn YH, Cho KJ, Na Y, Kim JS. Global sagittal alignment and clinical outcomes after 1-3 short-segment lumbar fusion in degenerative spinal diseases. *Asian Spine J*. 2022;16(4):551-559. doi:10.31616/asj.2021.0182

23. Sebaaly A, Gehrchen M, Silvestre C, et al. Mechanical complications in adult spinal deformity and the effect of restoring the spinal shapes according to the Roussouly classification: a multicentric study. *Eur Spine J*. 2020;29(4):904-913. doi:10.1007/s00586-019-06253-1

24. Kawabata A, Yoshii T, Sakai K, et al. Identification of predictive factors for mechanical complications after adult spinal deformity surgery: a multi-institutional retrospective study. *Spine*. 2020;45(17):1185-1192. doi:10.1097/brs.0000000000003500

25. Tobert DG, Davis BJ, Annis P, et al. The impact of the lordosis distribution index on failure after surgical treatment of adult spinal deformity. *Spine J*. 2020;20(8):1261-1266. doi:10.1016/j.spinee.2020.03.010

26. Mir JM, Galetta MS, Tretiakov P, et al. Achievement and maintenance of optimal alignment after adult spinal deformity corrective surgery: a 5-year outcome analysis. *World Neurosurg*. 2023;180:e523-e527. doi:10.1016/j.wneu.2023.09.106

27. Elias E, Bess S, Line B, et al. Outcomes of operative treatment for adult spinal deformity: a prospective multicenter assessment with mean 4-year follow-up. *J Neurosurg Spine*. 2022;37:607-616. doi:10.3171/2022.3.Spine2295