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Clinical Study

Predictors of serious, preventable, and costly medical complications in a population of adult spinal deformity patients

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Abstract

BACKGROUND CONTEXT: In 2008, the Centers for Medicare and Medicaid Services (CMS) established a list of hospital-acquired conditions (HACs) with significant deleterious effects on both patients and providers. Adult spinal deformity (ASD) surgery is complex and highly invasive, and as such may result in significant morbidity including these HACs.

PURPOSE: Identify predictors for developing the most common HACs among adult spinal deformity (ASD) patients undergoing corrective surgery.

STUDY DESIGN/SETTING: Retrospective analysis.

PATIENT SAMPLE: One thousand one hundred and seventy-one ASD patients.

OUTCOME MEASURES: HACs, Health-Related Quality of Life scores(HRQLs), Reoperation, Integrated Health State (IHS)

METHODS: ASD pts undergoing surgery (>18 years, scoliosis ≥20˚, SVA ≥5 cm, PT ≥25˚ and/or TK >60˚) with complete data at BL and up to 2 years post-op were included. Patients were stratified by presence of >1 HAC, defined as at least one superficial/deep SSI, UTI, DVT, or PE within a 30-day post-op window. Random forest analysis generated 5,000 Conditional Inference Trees to compute a variable importance table for top predictors of HACs. An area-under-the-curve (AUC) methodology compared normalized HRQL scores between groups to determine an IHS with 2-year follow-up.

RESULTS: Total of 1,171 pts (59.8 years, 76.2%F, 28.1kg/m^2) underwent corrective ASD surgery, with 1,053 pts in the non-HAC group and 118 in the HAC group. Of these pts, 25.4% had UTI, 15.4% DVT, 19.2% superficial SSI, 20.8% deep SSI, and 19.2% PE. HAC pts were on average older (63.5 vs 59.3, p=.004) and more often frail (51.3 vs 39.7%, p=.021) than non-HAC pts. Postop LOS and reoperation were most associated with HAC groups: [1] LOS >7 days [2] reoperation. Patient-related predictors of HACs were [3] age >50 yerr, [4] frailty, and [13] BMI >31. Procedure-related predictors of HACs were [5] operative-time >405 minutes, [6] levels fused >9, EBL >1450 mL, and [11] decompression. BL radiographic predictors were [7] PT >20˚, [9] PI-LL>6˚, [10] TL Cobb angle >15˚, [12] SVA C7-S1 >29 mm. No differences were observed between groups with regards to IHS ODI (0.73 vs 0.74, p=.863), SRS (1.3 vs1.3, p=.374), NRS Back (0.6 vs 0.6, p=.158). HAC had higher rates of reoperation than non-HAC (0.08 vs 0.01, p=.066), and any HAC within 30-days of index was a significant predictor of reoperation (OR: 2.448 [1.94−3.09], p<.001).

CONCLUSIONS: In a population of ASD patients, HACs were associated with length of stay, reoperation, age, and frailty. Radiographic parameters such as pelvic tilt >20˚, PI-LL >6˚, & SVA >29 mm also increased odds of HACs, and should raise postoperative awareness for HAC development.

Keywords: Adult spinal deformity; Hospital acquired conditions; Infection; Predictive modeling

Introduction

The Centers for Disease Control and Prevention recently reported that total national health expenditures in the United States amassed to $3.3 trillion, nearly 18% of the Gross Domestic Product in 2016. As the average age of Americans continues to rise, the economic burden on the healthcare system rises as well − calling for more emphasis on value-based care. Spine surgery is arguably at the forefront of this paradigm shift, with complex adult spinal deformity (ASD) procedures carrying higher upfront direct costs than other interventions such as lumbar discectomies or single-level anterior cervical discectomy and fusions [1]. Despite advances in surgical technique and clinical management, patients undergoing complex ASD-corrective surgery remain at increased risk for perioperative complications. Reported complications not only include those that are typically associated with spinal surgery such as Distal or Proximal Junctional Kyphosis and neurological complications, but also those associated with surgery and hospital stay in general.

These complications have been identified by the Centers for Medicare and Medicaid Services as preventable, non-reimbursable, hospital-acquired conditions (HACs) − also known as “never events” because they should ideally never occur under the appropriate clinical care [2]. Hence, in addition to reducing patient quality of life, HACs carry a significant financial burden on institutions, providers, and patients alike [3,4]. Prevention of such complications is therefore important in the delivery of care, and identifying their risk factors can help reduce future incidence.

The present study analyzed a large cohort of ASD patients undergoing elective spine surgery with a goal of identifying predictors for the most commonly reported HACs in this population: surgical site infection (SSI), venous thromboembolisms (deep venous thromboembolism, DVT or pulmonary embolus, PE), and urinary tract infections (UTI) [5,6]. Overall, it was our aim to bolster the practice of preventative medicine in adult spinal deformity and improve preoperative planning in this complex patient population. Acknowledgement of these findings within a risk stratification model context would assist the healthcare team in prioritizing post-surgical care and curb potential complications should patients meet certain criteria during their surgery or hospital stay.

Methods

Study design and data source

The present study is a retrospective review of prospectively collected data on consecutively enrolled ASD patients from 2008 to 2018. Patients were enrolled from 12 participating centers across the continental United States, and Institutional Board Approval was obtained at each site before the enrollment period. Nonoperative and operative ASD patients are included in the database, with the decision to operate based on thorough discussion between patient and enrolling clinician. Database inclusion criteria were patients ≥18 years presenting with ASD, defined by the following baseline radiographic presentation: coronal Cobb angle ≥20°, sagittal vertical axis (SVA, distance between C7 plumb line and sacral posterior superior margin) ≥5 cm, pelvic tilt ≥25°, and/or thoracic kyphosis >60°. Exclusion criteria weere spinal deformity secondary to neuromuscular, infectious, or malignant etiologies. Additional inclusion criteria for the present study included complete baseline radiographic data and perioperative (90-day) complication data as necessary.

Data collection and radiographic assessment

Patient demographic data included age, sex, body mass index (BMI), Charlson Comorbidity Index (CCI), and frailty index as assessed by the ASD-mFI [7]. Procedural data included surgical approach, fusion length, decompression presence and type, operative time in minutes, estimated blood loss (EBL), and length of stay (LOS) in days. Perioperative complication data included the presence of one or more of the following HACs within a 90-day window: SSI, UTI, DVT, and PE. All centers were responsible for reporting complications among their enrolled patients via chart review or as reported by patients during follow-up visits. These complications were the classified into the database by a centralized committee [8R, 9R].

Patient-reported outcome measures (PROMs) were administered and subsequently analyzed at baseline and follow-up intervals up to 2-years. These included the Oswestry Disability Index (ODI), Scoliosis Research Society-22 Questionnaire (SRS-22), and Numeric Rating Scales (NRS) for back and leg pain.

Radiographic assessment included the measurement of baseline global and regional sagittal and coronal alignment parameters, including the sagittal vertical axis from C7-S1 (SVA), cervical SVA from C2-C7, pelvic tilt (PT), mismatch of pelvic incidence (PI) minus lumbar lordosis (PI-LL), coronal Cobb angles of the thoracic, thoracolumbar (TL), and lumbar regions. All parameters were measured on standing posteroanterior and lateral radiographs using previously validated software (SpineView, ENSAM, Laboratory of Biomechanics, Paris, France) and measurement methodology (Lafage et al).

Statistical analysis

To assess predictors of HAC's in our cohort of operative ASD patients, patients were grouped by presence of at least one (≥1) HAC as described above. Random forest analysis generated 5,000 Conditional Inference Trees to compute a variable importance table for top predictors of the HAC group, with baseline radiographic parameters, perioperative outcome measures, and demographics included. Top patient-related, procedural, complication, and radiographic predictors were determined, and cut-off values were established (through iterations of multivariate regression equations) at which predictors have a global effect. Demographic, surgical, and perioperative factors were summarized with descriptive analyses and compared across HAC groups using independent samples *t*-tests and chi-squared tests, as appropriate. Paired samples *t*-tests analyzed pre to post-op differences (up to 2 years) in sagittal alignment parameters and HRQL measures for the entire ASD cohort and across HAC groups. Random forest analysis and Conditional Inference Tree generation was conducted using R software (v3.5, Auckland, New Zealand); otherwise, all statistical analyses were conducted using SPSS software (v23.0, Armonk, NY, USA).

A subanalysis assessed the overall postoperative recovery process up to 2 years. Patient HRQL outcomes were normalized, plotted, and assessed using a previously published area-under-the-curve methodology [8]. HRQL outcomes from all study intervals (baseline, 6-week postoperative, 1-year, 2-year) were divided by baseline score per patient, resulting in a normalized baseline score of 1, and postoperative scores <1, =1, or >1, depending on improvement or deterioration. Normalized HRQL scores were then plotted against time and lines connected normalized HRQL values between time points, yielding a series of “recovery trapezoids.” The areas of these trapezoids were calculated and summed to obtain a total follow-up area-under-the-curve, which was then divided by the total follow-up time to generate an “integrated health state” (IHS). IHS serves as an outcome metric to assess the entire process of improvement or deterioration in health-related quality of life across the whole recovery timeline.

Results

ASD cohort overview

Overall, 1,171 operative ASD patients met inclusion criteria (59.8 years, 76.2% female, 28.1 kg/m^2). The cohort

Table 1
Changes in alignment and HRQL metrics for the entire ASD cohort (N=1,171) from pre to post-op at 2-years

Overall ASD cohort alignment correction			
	Pre-Op	2Y Post-Op	p
C7-S1 SVA	62.4±73.1	28.0±54.0	<.001*
PT	23.9±10.9	21.4±10.1	<.001*
PI-LL	14.7±23.9	2.39±18.4	<.001*
Sacral Slope	29.8±15.9	32.4±15.6	<.001*
C2-C7 SVA	28.8±14.9	30.9±14.0	<.001*
T1 Slope	28.9±13.8	32.4±13.5	<.001*
Overall ASD cohort HRQL outcomes			
	Pre-Op	2Y Post-Op	p
ODI	43.9	27.9	<.001*
SRS Total	2.78	3.66	<.001*
EQ5D	0.753	0.805	<.001*
SF-36 Physical Function	30.49	37.76	<.001*
NRS Back Pain	7.18	3.67	<.001*
NRS Leg Pain	4.81	2.65	<.001*

* indicates statistical significance at p<0.05.

presented at baseline with overall moderate pelvic retroversion (PT: 24.2±10.7°), thoracolumbar deformity (PI-LL: 16.8±22.7°), and global sagittal malalignment (SVA: 69.5±72.7). Surgical correction of ASD resulted in improved overall cohort alignment, with PT (21.4±10.1°), PI-LL (2.39±18.4°), and SVA (28.0±54.0 mm) improving significantly at 2-year follow-up compared with baseline (all p<.001) (Table 1).

Mean levels fused anteriorly was 2.56±2.1 and mean levels fused posteriorly was 10.64±4.5, with a mode upper instrumented vertebrae (UIV) at T10 and a mode lower instrumented vertebrae (LIV) at pelvis. 63.2% of patients underwent interbody fusion (IBF), with 36.2% undergoing single level IBF, 39% undergoing 2−3 level IBF, and 24.6% undergoing four or more level IBF. 58.5% required decompression, and 53.6% underwent Smith-Peterson osteotomy, 15.5% underwent pedicle subtraction osteotomy, 66.6% underwent 3-column osteotomy, and 3% underwent vertebral column resection.

In our overall cohort, 59.9% of patients had at least one documented postoperative complication, the most common of which was neurologic, followed by radiographic and implant-related. Around 20.8% of patients experienced a major complication, defined as a complication that resulted in significant deviation from the standard of care.

Clinical outcomes for the entire ASD cohort significantly improved following surgical realignment and correction of thoracolumbar deformity, as shown by superior HRQL scores at 2-year follow-up: ODI decreased (43.9 vs 27.9), EQ5D increased (0.753 vs 0.805), SRS Total increased (2.78 vs 3.66), NRS Back pain decreased (7.18 vs 3.67) and NRS Leg pain decreased (4.81 vs 2.65) (all p<.001) (Table 1).

HAC groups

One hundred and eighteen patients had ≥1 HAC and 1,053 patients did not (Non-HAC). Within the HAC cohort, 25.4% of patients experienced a UTI, 15.4% experienced a DVT, 19.2% experienced a superficial SSI, 20.8% experienced a deep SSI, and 19.2% experienced a PE. On average, patients in the HAC cohort were older (63.5 vs 59.3 years, p=.004) and more frail (p=.049) than patients in the non-HAC group (Table 2).

Surgical approach did not differ significantly between groups, with posterior, anterior, and combined approaches utilized at similar rates (all p>.05). There were no differences in osteotomy types, including Smith-Peterson osteotomy (p=.990), three-column osteotomy (p.862), and corpectomy (p=.862). Estimated blood loss (EBL) (p=.011), operative time (p=.001), length of stay (LOS) (p<.001), and levels fused (p<.001) were higher in the HAC group compared with the Non-HAC group. Rate of revision surgery was also significantly higher in HAC patients (39.8% vs 15.5%, p<.001) (Table 2).

HAC predictors

Random forest analysis (RFA) followed by conditional inference tree analysis generated a variable importance table with statistically significant cut-offs for top patient-related, procedure-related, and alignment-related predictors

Table 2
Patient demographics, procedural factors, and baseline radiographic parameters in HAC vs Non-HAC cohorts

	Non-HAC	HAC	p
Demographics			
Age (years)	59.4±15	63.2±10	<.001*
Gender (%F)	73.2%	79.3%	.181
BMI (kg/m^2)	28.0±9.0	28.9±6.0	.301
CCI	1.66±1.7	1.91±1.6	.128
ASD-mFI	0.25±0.18	0.28±0.17	.049*
Procedural factors			
Posterior only approach	65.0%	61.9%	.543
Anterior only approach	0.47%	0.85%	.591
Combined approach	32.3%	37.3%	.301
EBL (cc)	1407.6	1759.0	.011*
Optime (min)	366.3	409.6	.001*
Length of stay (days)	7.46	10.9	<.001*
Levels fused	10.46	12.21	<.001*
Smith-Peterson osteotomy	2.78	2.78	.990
Pedicle subtraction osteotomy	0.15	0.19	.259
3-column osteotomy	2.98	3.03	.862
Corpectomy	0.01	0.01	.791
Revision	15.5%	39.8%	<.001*
Baseline radiographics			
Pelvic tilt	23.8±10.7	27.3±9.8	.005*
PI-LL	16.2±23.0	22.0±20.3	.010*
C7-S1 SVA	67.3±72.4	87.8±72.9	.006*
Sacral slope	30.9±14.5	30.2±11.1	.597
Thoracic coronal cobb	28.8±20.0	29.0±22.0	.940
Lumbar coronal cobb	23.8±10.7	27.3±9.8	.330

* indicates statistical significance at p<0.05.

for HACs. Overall, procedure-related predictors were the top category of predictors: [1] inpatient length of stay >7 days and [2] reoperation. Patient-related predictors were the second strongest category of predictors: [3] age greater than 50 years and [4] frail patient (as defined by a modified frailty index (mFI) greater than 0.3). In terms of baseline radiographic (alignment-related) predictors, a [7] pelvic tilt greater than 20^o, [9] PI-LL greater than 6^o, and [10] thoracolumbar coronal Cobb angle greater than 15^o were the strongest predictors of HACs (Table 4).

Other predictors included operative time greater than 405 minutes, long-construct fusions greater than 9 levels, EBL greater than 1,450 mL, decompression, and BMI greater than 31kg/m^2 (Table 4).

HAC predictors following multivariable forward conditional regression

All significant predictors from the RFA listed above were input into a multivariable forward conditional regression equation, which controlled for potential confounders between HAC and non-HAC groups (age, frailty index, levels fused). The model created was a simplified list of pertinent predictors, including only those statistically significant predictors with an independent effect on HAC probability.

Length of stay greater than 7 days, decompression, reoperation, baseline coronal thoracolumbar Cobb angle greater than 15^o, and EBL greater than 1,450mL were the top independent predictors of the HAC group, respectively.

Two-year integrated health state outcomes

An Integrated Health State (IHS) calculation was done for patients with complete consecutive clinical outcomes data at baseline, 6 month, 1-year, and 2-year time points. In terms of IHS for ODI, HAC and non-HAC groups did not differ significantly (0.74 vs 0.73, p=.863). There were also no significant differences in IHS for Total SRS (1.27 vs 1.31, p=.374), IHS for NRS Back pain (0.64 vs 0.58, p=.158), and IHS for NRS Leg pain (0.67 vs 0.67, p=.977) (Table 3).

Table 3
Baseline, 2-year, and Integrated Health State HRQL scores across HAC groups

	Non-HAC	HAC	p
Baseline HRQL Raw Scores			
ODI	44.7	49.4	.008*
SRS total	2.75	2.65	.122
EQ5D	0.74	0.74	.566
SF-36 Physical Function	30.1	27.1	.006*
NRS back pain	7.17	7.63	.013*
NRS leg pain	4.70	5.30	.074
2-year HRQL Raw Scores			
ODI	27.6	30.3	.351
SRS total	3.66	3.61	.635
EQ5D	0.80	0.80	.735
SF-36 Physical Function	38.1	35.2	.081
NRS back pain	3.66	3.70	.924
NRS leg pain	2.57	2.64	.861
Integrated Health State (IHS)			
ODI	0.742	0.733	.863
SRS total	1.274	1.305	.374
NRS back pain	0.638	0.575	.158
NRS leg pain	0.675	0.672	.977

* indicates statistical significance at $p<0.05$.

Discussion

The CMS initiative in 2008 was an important catalyst for value-based care, shifting the financial onus of specific HACs from the patient onto healthcare providers and institutions. HACs are costly, with previous studies reporting an estimated cost of $13,891 per DVT or thrombophlebitis case, $18,256 per deep SSI, and $14,321 per UTI [5,9]. Being able to identify patients who may be more pre-disposed to such HACs thus provides a dual benefit for patients and providers alike. Adult spinal deformity (ASD) represents a spectrum of debilitating coronal and sagittal malalignment with a variety of etiologies, including degenerative scoliosis, adult scoliosis, and iatrogenic causes [10−12]. As surgical correction of ASD continues to rise in utility, so too does the associated morbidity burden − with complication rates reported as high as 80% in ASD literature [10,13,14].

The present study retrospectively analyzed a prospective database of consecutively enrolled surgical ASD patients to identify categorical and individual predictors of three of the most commonly reported HACs in spine surgery: UTI, SSI (superficial or deep), and VTE (deep venous thromboembolism or pulmonary embolism) [5]. Our study found an overall HAC rate near 10%, which is significantly higher than previously published rates in spine surgery [15]. This may reflect the incredibly complex and severe nature of our cohort’s deformity at baseline (Table 1), which requires highly invasive operations of longer durations. Our individual HAC rates corroborated previous findings identifying SSI as the most common early post-operative complication in spine surgery [15−17]. Our main objective − accomplished through machine learning (specifically, random forest analysis which generated 5,000 conditional inference trees or iterations of multivariable regression equations) − was to identify top patient-related, procedure-related, and radiographic-related predictors of HAC development within a 90-day perioperative window. We also utilized an Integrated Health State (IHS) methodology (see Methods) with 2-year HRQLs to compare patient recovery kinetics in those who experienced one or more HAC with those who did not (non-HAC). A greater understanding of the risk associated with surgical and hospital-related events as explored by this study would potentially alert care providers of potential complication occurrence and allow for prioritization of preventative measures.

Numerous predictors of HACs were identified in patients undergoing corrective ASD surgery. Overall, the strongest category of predictors was "procedure-related", followed by the "patient-related" category and "radiographic-related" category, respectively. Within procedure-related predictors, extended length of stay >7 days and reoperation were the top two predictors, a finding that may reflect an innate relationship between HACs and the variables themselves. Decompression, including the use of osteotomy, was also found to be a significant predictor − increasing odds of HACs by 2.33 times compared with those patients without decompression. Di Capua et al. found in their NSQIP analysis of 30-day perioperative data that osteotomy increased odds of HACs by a factor of 1.61 [18]. This is not surprising in light of recent findings of the literature showing various complication profiles associated with osteotomy type [10,11,19−22]. Smith et al. analyzed early complications in 23 adult cervical deformity patients who underwent three-column osteotomy (3CO), including pedicle subtraction osteotomy (PSO) and vertebral column resection (VCR), and found that 56.5% of patients had ≥1 complication including neurologic deficit (most common), infection, distal junctional kyphosis (DJK), and cardiorespiratory failure [23]. In another study of 578 thoracolumbar deformity cases, Smith et al. found that osteotomy patients who underwent PSO or VCR had significantly higher complication rates (wound infection, implant failure, neurologic deficit) than those who did not, and that more aggressive osteotomies were associated with progressively higher complication rates [24].

Prolonged operative times greater than 405 minutes increased odds of HACs by 2.24 times compared with shorter operations. Although previous studies have reported similar findings with operative times ≥4 hours increasing risk for HACs, our cut-off is higher likely due to severe cohort malalignment which demands more advanced deformity correction [18]. Fogarty et al. prospectively reported an increase in SSI associated with prolonged operative times > 6 hours due to increased bacterial inoculation at the incision site coupled with decreased tissue perfusion [25]. A study by Procter et al. found that operative duration was independently associated with increased infectious complications such as SSI and UTI, controlling for patient and procedure-related risk factors [26]. Interestingly, both infectious complications and LOS increased geometrically at a rate of 6% per every additional half-hour of operative time.

In addition to procedure-related factors, patient-related factors were an important category of HAC predictors, with age greater than 50, frailty, and BMI over 31 all significantly increasing odds of developing one or more HAC. Although advanced age has long been known to predispose patients to higher post-operative complication rates and a prolonged recovery course, frailty status is a relatively newer metric of physiologic reserve that has shown superiority in predicting patient outcomes [27,28]. A 40-factor modified frailty index for ASD patients (ASD-mFI) has been validated for use in this uniquely complex group of patients, with a score of 0.3 to 0.5 indicating frailty and a score >0.5 indicating severe frailty [7]. We found that an ASD-mFI >0.3 (indicating frailty status, at minimum) increases odds of HACs by a factor of 1.6 compared with nonfrail patients. Since the ASD-mFI takes into account functional status and ability to perform activities of daily living (ADLs), patients with higher frailty cannot adequately mobilize after surgery and may thus be predisposed to continued blood stasis and ultimately higher rates of VTEs and other HACs [29,30].

Radiographic predictors of HACs included sagittal (SVA>29mm, PI-LL>6°, PT>20°) and coronal (TL Cobb angle>15°) malalignment at baseline. To our knowledge, no previous studies have found significant radiographic predictors of HACs in a surgical ASD cohort. On the other hand, the literature is rich in correlating radiographic malalignment to patient clinical outcomes and inferior HRQLs [31−34] Glassman et al. found that sagittal positive imbalance was the most important predicator of inferior patient HRQLs in terms of SF-12, ODI, and SRS-29 scores, whereas coronal malalignment was less important. Not surprisingly, our findings following random forest analysis of a comprehensive list of sagittal and coronal modifiers suggest that sagittal malalignment plays a more robust role in perioperative HAC development as well, with 3 out of 4 significant radiographic predictors in the sagittal plane (Table 4). Despite such findings, we must also consider that patients with greater radiographic malalignment at baseline likely required more invasive, aggressive correction, which may simultaneously increase risk for HAC development.

We did not find differences in Integrated Health State (IHS) between HAC and non-HAC groups (Table 3). This is important in a bigger picture context, especially given the fact that our overall ASD cohort reported significantly improved quality of life up to 2-years after surgical correction of their deformity (improved ODI, SRS-22, SF-36, NRS Back and Leg pain scores, see Table 1). This may be due to timing of HACs and, in a sense, reflects a limitation of our data as we were not able to capture short-term, perioperative HRQL scores while the patient was still in the hospital.

Further limitations of our study include the retrospective nature of our analysis, which can reduce the amount of detail gathered during data collection. In addition, the nature of our analysis did not allow us to establish causality from one variable to the next: for example, while an increased length of stay may indeed predispose patients to a higher risk of HACs during their hospital stay, it may simultaneously hold true than HACs increase the risk for an extended length of stay. The use of the Integrated Health State also carries limitations, as it linearizes the recovery process which does not account for the fluctuation of improvements and deteriorations over time. This methodology is also limited to the follow-up points collected, which reduces the granularity of the analysis. Additionally,

Table 4
Categories of patient-related, procedural, and radiographic predictors for the HAC group (N=118)

Overall rank	Factor associated with HAC	Groups compared: 1 (N) vs 2 (N)	Proportion of HAC to non-HAC		p value	O.R.	95% Confidence interval	
			HAC	No HAC			Lower	Upper
Baseline patient-related predictors								
4	Frail patient	Yes (427) vs No (368)	51.3%	39.7%	.018	1.60	1.08	2.36
3	Age ≥50 years	<50 (195) vs ≥50 (846)	92.2%	79.9%	.002	2.96	1.47	5.96
13	BMI >31	<31 (773) vs ≥31 (259)	36.0%	23.7%	.005	1.80	1.20	2.72
Procedural predictors								
5	Operative time >405 mins	≤405 (628) vs >405 (400)	56.5%	36.7%	<.001	2.24	1.52	3.32
11	Decompression	Yes (608) vs No (424)	75.4%	56.9%	<.001	2.33	1.49	3.64
2	Reoperation	Yes (199) vs No (842)	40.0%	16.5%	<.001	3.37	2.23	5.08
6	Levels fused >9	≤9 (332) vs >9 (691)	80.7%	65.9%	.002	2.16	1.33	3.52
1	Postoperative LOS >7 days	≤7 (662) vs >7 (376)	60.9%	33.2%	<.001	3.14	2.11	4.67
8	Estimated blood loss >1,450 mL	≤1,450 (701) vs >1,450 (326)	50.9%	29.4%	<.001	2.49	1.68	3.70
Baseline radiographic predictors								
9	PI-LL >6°	<6° (318) vs ≥6° (721)	83.3%	67.7%	.001	2.39	1.43	3.98
12	SVA C7-S1 >29 mm	<29 (329) vs ≥29 (693)	80.0%	66.3%	.004	2.03	1.25	3.30
7	PT >20°	<20° (349) vs ≥20° (690)	66.4%	33.6%	.002	2.15	1.34	3.47
10	TL Coronal Cobb Angle >15°	≤ (236) vs >15° (584)	83.7%	69.6%	.006	2.24	1.26	3.98

differences in individual patient management such as urinary catheter placement, use of post-operative anticoagulants or compression stockings, or intraoperative antibiotic dosing could not be controlled for. However, this limitation can also be considered a potential strength, with a multicenter analysis allowing for greater applicability than that of one institution or surgeon.

Conclusions

In a cohort of 1,171 ASD patients undergoing surgical correction, the top categories of HAC predictors were procedure-related, patient-related, and radiographic-related factors, respectively. Important predictors included osteotomy, increased patient frailty status, longer operative times, and positive sagittal imbalance − including greater pelvic tilt, sagittal vertical axis, and mismatch of pelvic incidence to lumbar lordosis. Despite these factors increasing odds of HAC development, no differences in long-term disability or overall quality of life were found between HAC and non-HAC groups. Our findings can help increase surgical awareness in an already complex ASD patient population, and may prove instrumental in delivering a higher standard of care at both clinical and administrative platforms.

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Declarations of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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