The comprehensive anatomical spinal osteotomy and anterior column realignment classification

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OBJECTIVE Spinal osteotomies and anterior column realignment (ACR) are procedures that allow preservation or restoration of spine lordosis. Variations of these techniques enable different degrees of segmental, regional, and global sagittal realignment. The authors propose a comprehensive anatomical classification system for ACR and its variants based on the level of technical complexity and invasiveness. This serves as a common language and platform to standardize clinical and radiographic outcomes for the utilization of ACR.

METHODS The proposed classification is based on 6 anatomical grades of ACR, including anterior longitudinal ligament (ALL) release, with varying degrees of posterior column release or osteotomies. Additionally, a surgical approach (anterior, lateral, or posterior) was added. Reliability of the classification was evaluated by an analysis of 16 clinical cases, rated twice by 14 different spine surgeons, and calculation of Fleiss kappa coefficients.

RESULTS The 6 grades of ACR are as follows: grade A, ALL release with hyperlordotic cage, intact posterior elements; grade 1 (ACR + Schwab grade 1), additional resection of the inferior facet and joint capsule; grade 2 (ACR + Schwab grade 2), additional resection of both superior and inferior facets, interspinous ligament, ligamentum flavum, lamina, and spinous process; grade 3 (ACR + Schwab grade 3), additional adjacent-level 3-column osteotomy including pedicle subtraction osteotomy; grade 4 (ACR + Schwab grade 4), 2-level distal 3-column osteotomy including pedicle subtraction osteotomy and disc space resection; and grade 5 (ACR + Schwab grade 5), complete or partial removal of a vertebral body and both adjacent discs with or without posterior element resection. Intraobserver and interobserver reliability were 97% and 98%, respectively, across the 14-reviewer cohort.

CONCLUSIONS The proposed anatomical realignment classification provides a consistent description of the various posterior and anterior column release/osteotomies. This reliability study confirmed that the classification is consistent and reproducible across a diverse group of spine surgeons.

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KEYWORDS osteotomy; spine deformity; minimally invasive surgery; spine surgery; scoliosis; XLIF; LIF

ABBREVIATIONS ACR = anterior column realignment; ALL = anterior longitudinal ligament; FEA = finite element analysis; LIF = lumbar interbody fusion; LL = lumbar lordosis; MIS = minimally invasive surgery; PCO = posterior column osteotomy; PI = pelvic incidence; SVA = sagittal vertical axis.

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SAGITTAL malalignment and spinopelvic disharmony contribute significantly to pain and disability in patients with spinal deformities caused by scoliosis, degeneration, and iatrogenic flat-back syndrome.^{13,28} In addition to decompression, instrumentation, and fusion, realignment of the spine has gradually become recognized as an indispensable part of surgical intervention for patients with spinal deformities. The goals of surgery to achieve harmonious spinal alignment are correction of sagittal vertical axis (SVA) < 5 cm, pelvic tilt < 25°, and lumbar lordosis (LL) within 10° of the pelvic incidence (PI).^{5,12,13,15,18,28,29} Traditionally, varying posterior shortening osteotomies were performed to release and reconstruct the spine to achieve appropriate sagittal alignment and spinopelvic harmony. Schwab et al. recently classified osteotomies from the posterior approach.²⁷ The classification is anatomically based with graduated complexity that ranges from simple inferior facet resection to those including pedicle subtraction osteotomy and vertebral column resection at 1 or more levels.

Minimally invasive surgery (MIS) via anterolateral lumbar interbody fusion (LIF) has gained significant popularity in the past decade. Initially used for degenerative spinal diseases with the goal of indirect decompression and interbody fusion, the technique has since been added to the spine surgeon's armamentarium to treat adult spinal deformity. The anterior column realignment (ACR) procedure is an extension of anterolateral LIF that incorporates division of the anterior longitudinal ligament (ALL), allowing greater manipulation of the anterior and middle columns across the disc space, which can be further extended into the vertebral body through a partial or complete vertebrectomy.^{11,38} When combined with a posterior release, ACR allows manipulation of all 3 columns of the spine.^{32,33,39} As a result, ACR has enabled minimally invasive strategies to be performed to correct spinal deformities that previously were only treatable through open posterior-based surgeries reliant on osteotomies.^{1,26}

Whether to facilitate communication regarding surgical planning, clinical research, or medicofinancial coding, a comprehensive anatomical realignment classification of ACR/osteotomy is needed. In this study, we propose a classification system that provides surgeons with a reference to achieve desired lordosis with varying degrees of anterior column release and osteotomies of the spinal column. This reference is a supplement to the Schwab spinal osteotomy classification and is intended to be anatomically based and comprehensive. The goal of this classification system is to lay the foundation for a common surgical anatomical nomenclature to facilitate communication and research in adult spinal deformity.

Methods

Supplemental ACR Classification

We divided the possible combinations of ACR with posterior column osteotomies (PCOs) into 6 anatomical grades of anterior column realignment (Fig. 1), each with a concurrent form of PCO according to the well-established Schwab osteotomy classification. Increasing grades of ACR denote a greater extent of posterior column resec-

tion. Likewise, an increasing grade reflects more destabilization and potential for segmental lordosis correction (Fig. 1). Furthermore, surgical approach modifiers are added to describe anterior only, posterior, or combined approaches.

Classification Reliability

To evaluate the clarity and reliability of the proposed classification system, a single-center database was retrospectively analyzed to create an ACR case series for evaluation. This study was conducted with institutional review board approval for waiver of patient informed consent. Identified cases were chosen to represent a wide range of ACR grades. Preoperative and postoperative sagittal and coronal standing scoliosis radiographs were collected to create illustrative surgical cases. These cases were then integrated into Power Point slides and mixed in random order with a brief operative note following each clinical scenario. A group of 14 orthopedic and neurological surgeons trained in complex spine surgery across multiple institutions then assigned the cases an ACR grade according to the proposed classification system in a blinded fashion to assess interrater reliability. Approximately 2 weeks after the first grading session, the process was repeated with the same cases in a different order to assess intraobserver reliability.

Interobserver and intraobserver reliability were then measured by calculating weighted Fleiss kappa values using IBM SPSS (version 20.0, IBM Corp.). Kappa values of 0.00 to 0.20 were considered slight agreement, 0.21 to 0.40 fair agreement, 0.41 to 0.60 moderate agreement, 0.61 to 0.80 substantial agreement, and 0.81 to 1.00 almost perfect agreement.^{19,27}

Review of the Literature

To evaluate established evidence on the usage and anatomical consequences of ACR with or without PCOs, a systematic review of the literature was performed. We reviewed PubMed and MEDLINE for abstracts and studies examining the ACR technique and its clinical experience since September 2017 through a search for terms "anterior column realignment/release/resection." Two reviewers (J.S.U. and D.S.X.) screened identified studies by their title and abstracts for inclusion in the analysis. If it could not be determined whether an article should be included on the first pass, the entire article was reviewed for inclusion. All selected articles were then assessed for data related to segmental lordosis change, osteotomy type, and cage type measurements. Studies with incomplete data were excluded, and all collected information was summarized for additional analysis.

Results

Literature Review

Thirteen studies on ACR were identified, of which 9 included all necessary variables for analysis (Table 1). Data relevant to each specific ACR classification grade are summarized with the relevant ACR grade described below.

ACR Classification	Construct	Schwab Modifier	Approach Modifier
Grade A		0	Lateral or Anterior
Grade 1		1	Lateral or Anterior or Posterior
Grade 2		2	
Grade 3		3	
Grade 4		4	
Grade 5		5	

FIG. 1. ACR classification overview. A diagram of the proposed ACR classification with illustrations of each grade's construct, the bony Schwab modifier that defines each grade, and the available approach modifiers. Artwork used with permission from Barrow Neurological Institute.

Description of Classification and Literature Evidence

Figure 1 provides an overview of the ACR classification grading system. A total of 6 grades exist, ranging from A to 5. Each grade is determined by a Schwab modifier that denotes how much posterior column destabilization is applied to facilitate additional gains in segmental lordosis, as well as an approach modifier, which denotes whether the ALL was released from an anterior, lateral, or posterior approach.

Grade A ACR: ALL Release With Hyperlordotic Cage and Intact Posterior Elements

Description

A grade A ACR (Fig. 2) involves releasing the ALL

without performing any shortening osteotomies posteriorly. The approach is lateral or anterior, and a 20° or 30° hyperlordotic cage is used depending on the amount of segmental lordosis restoration desired and the accessibility of the disc space. Approximately 7.8° of segmental lordosis, with a range of 1°–14°, can be gained with a 30° cage.

Published Techniques Associated With Grade A ACR

Several publications described ACR without posterior osteotomies and all reported similar degrees of segmental lordosis restoration depending on the angle of the interbody. In the beginning of ACR utilization during 2012, Deukmedjian et al. and Uribe et al. showed a change of 7.5° to 11° and 10.6° to 13.1° in segmental lordosis correction,

TABLE 1. Summary of lateral ACR literature

ACR Grade	Authors & Year	Type of Study	Posterior Osteotomy	Implant Lordosis	Segmental Lordosis Change (mean or range)
A	Uribe et al., 2012 ³⁸	Cadaveric study	None	20°	9.1–9.5°
	Melikian et al., 2016	Cadaveric study	None	20°	12°
	Uribe et al., 2015	FEA	None	20°	14.5–19.5°
	Demirkiran et al., 2016	Retrospective case series	None	20°	8.7°
	Manwaring et al., 2014	Retrospective case series	None	20°	12°
	Uribe et al., 2012 ³⁸	Cadaveric study	None	30°	10.6–13.1°
	Uribe et al., 2015	FEA	None	30°	19.5–22.5°
	Deukmedjian et al., 2012 ¹¹	Retrospective case series	None	30°	7.5–11°
1	Uribe et al., 2015	FEA	Inferior facetectomy	20°	21–23°
	Uribe et al., 2015	FEA	Inferior facetectomy	30°	22.5–26°
	Demirkiran et al., 2016	Retrospective case series	Inferior facetectomy	30°	14.2°
	Turner et al., 2015	Retrospective multicenter case series	Inferior facetectomy or complete facetectomy	20 or 30°	15.4–18.2°
	Uribe et al., 2015	FEA	Complete facetectomy	20°	24–25°
2	Akbarnia et al., 2014	Retrospective case series	Complete facetectomy	20°	22–24°
	Uribe et al., 2015	FEA	Complete facetectomy	30°	32–33°
	Berjano et al., 2015	Retrospective case series	Complete facetectomy	30°	24–35°
	Akbarnia et al., 2014	Retrospective case series	Complete facetectomy	30°	8–47°
	Uribe & Mundis	Personal cases	Pedicle subtraction osteotomy	30°	46°
3 & 4	Mundis	Personal case	Vertebral body corpectomy	Expandable 0° cage	48°

respectively, for a 30° cage.^{10,11,38} Uribe et al. also showed 9.1°–9.5° of segmental lordosis restoration for 20° cages.³⁸ Manwaring et al. and Melikian et al. both showed an average of 12° of correction in segmental lordosis for grade A ACR with 30° hyperlordotic cages.^{20,21} Later, Uribe et al. performed a finite element analysis (FEA) with 20° and 30° cages, demonstrating a range of 14.5°–19.5° of segmental lordosis correction for 20° cages and 19.5°–22.5° of correction for 30° cages.³⁷

Grade 1 ACR: ALL Release With Hyperlordotic Cage and Inferior Facetectomy (Schwab grade 1)

Description

A grade 1 ACR comprises an ALL release with application of an intervertebral cage combined with resection of the inferior facet and joint capsule at a given spinal level with or without interspinous ligament resection (Fig. 3). Approximately 13.1° of segmental lordosis (range 3°–26°) can be gained with grade 1 and a 30° cage.

Published Techniques Associated With Grade 1 ACR

Demirkiran et al. described ACRs combined with adjacent partial facetectomies with either 20° or 30° hyperlordotic cages. Changes in segmental lordosis restoration averaged 8.7° for 20° cages and 14.2° for 30° cages.⁹ Turner et al. described ACRs with either partial or complete facetectomies; however, they did not specify the cage size. They reported a change in segmental lordosis restoration ranging from 15.4° to 18.2°.³⁵ The FEA of Uribe et al. showed a correction of 21°–23° in segmental lordosis for 20° cages and 22.5°–26° of segmental lordosis correction for 30° cages.³⁷

Grade 2 ACR: ALL Release With Hyperlordotic Cage and PCO (Schwab grade 2)

Description

A grade 2 ACR involves ALL release with the addition of a hyperlordotic cage combined with both superior and inferior facet resection at a given spinal segment. Additionally, the interspinous ligament, ligamentum flavum, and other posterior elements of the vertebra, including the lamina and the spinous process, may also be resected (Fig. 4).

Published Techniques Associated With Grade 2 ACR

Berjano et al. described ACR with 30° hyperlordotic cages and Schwab grade 2 PCOs with subsequent segmental correction ranging between 24° and 35°.⁶ Akbarnia et al. described 22°–24° of correction for 20° cages and 8°–47° of correction for 30° cages.¹ Uribe et al.'s FEA analysis showed 24°–25° changes in segmental lordosis for 20° cages and 32°–33° changes for 30° cages with PCO.³⁷ The average segmental lordosis gained was 22.6° for Grade 2 ACRs with a 30° hyperlordotic cage (range 8°–47°).

Grade 3 and 4 ACRs: ALL Release With Hyperlordotic Cage and 3-Column Osteotomy (Schwab grades 3 and 4)

Description

Grade 3 and 4 ACRs incorporate an adjacent 3-column osteotomy, including pedicle subtraction osteotomies and wedge vertebral body resections. For grade 3 ACR, the 3-column osteotomy occurs through the adjacent vertebral body alone (Fig. 5). In a grade 4 ACR, the 3-column osteotomy is placed 2 vertebrae distal to the ACR implant, and the

FIG. 2. Grade A ACR. ALL release with hyperlordotic cage and intact posterior elements. Lateral (A) and posterior (B) views of the construct, showing that no posterior bony work has been done. Anteroposterior (C and D) and lateral (E and F) standing radiographs obtained in a patient who underwent a stand-alone lateral Grade A ACR at L4–5. Panels A and B used with permission from Barrow Neurological Institute.

cuts run through the distal adjacent disc space for additional gains in segmental lordosis (Fig. 5). There are no published data regarding grade 3 and 4 ACR, but on a geometrical basis, we believe that if a correction of more than 30° is necessary, a grade 3 ACR or higher should be considered.

Grade 5 ACR: Vertebrectomy With ALL Release

Description

Grade 5 ACR is the complete or partial removal of a vertebral body and both adjacent discs through a lateral, anterior, or posterior approach (Fig. 6). If the ACR occurs in the thoracic spine, rib head resection is also required. A Grade 5 ACR can involve the vertebral body and disc resection alone, or incorporate different amounts of posterior column resection.

Published Techniques Associated With Grade 3–5 ACR

Unfortunately, because of the scarcity of severe deformity cases requiring these aggressive surgical maneuvers, we could use only isolated case reports and observational studies from our clinical experience as a reference. These limited examples demonstrate that a change in segmental lordosis with gains greater than 40° is achievable through grade 3–5 ACRs. There are not enough published data to quantify a definitive range of radiographic outcomes that are achievable.

Interobserver and Intraobserver Reliability

Data from a total of 16 patients were collected and composed into surgical cases for rating reliability analysis. Four cases were classified as grade A, 4 cases as

FIG. 3. Grade 1 ACR: ALL release with hyperlordotic cage and inferior facetectomy. Lateral (**A**) and posterior (**B**) illustrations of the construct showing release of the ALL and complete bilateral inferior facetectomies. Anteroposterior (**C** and **D**) and lateral (**E** and **F**) standing radiographs demonstrating a T11–S1 revision construct with an anterior grade 1 ACR at L5–S1 and a grade A ACR at L4–5. Panels A and B used with permission from Barrow Neurological Institute.

grade 1, 4 cases as grade 2, 2 cases as grade 3, and 2 cases as grade 4.

The interobserver reliability of the ACR grade (without the modifiers) was rated as “almost perfect” with a corresponding weighted Fleiss kappa coefficient average of 0.98 and 95% CI of 0.96–0.99. Within literature standards, kappa values greater than 0.75 are considered to have a high degree of agreement beyond chance.⁷ Values below 0.40 have a low degree of agreement and values between 0.40 and 0.75 represent a fair to good level of agreement beyond chance alone. When both modifiers are included, weighted kappa decreased slightly to 0.96 or 96% agreement; however, this is still considered “near perfect” reliability.

When the order of the 16 cases was re-randomized and reviewed again by our 14 surgeons 2 weeks later, the intraobserver weighted Fleiss kappa coefficient was 0.98 with a 95% CI of 0.97–0.99, suggesting excellent intraobserver consistency.

Discussion

Compared with open surgical techniques, MIS for degenerative spinal conditions has demonstrated decreased blood loss, length of stay, and risk of infection, while also preserving paraspinal musculature.^{23,40} However, early application of MIS for the treatment of spinal deformi-

FIG. 4. Grade 2 ACR: ALL release with hyperlordotic cage and complete facetectomies. Lateral (**A**) and posterior (**B**) illustrations of the construct showing release of the ALL and complete bilateral superior and inferior facetectomies. Anteroposterior (**C and D**) and lateral (**E and F**) standing radiographs demonstrating a posterior grade 2 ACR at L2–3 to correct a focal kyphotic deformity. Panels A and B used with permission from Barrow Neurological Institute.

ties was limited due to inadequate restoration of sagittal spinopelvic imbalance and PI-LL mismatch.^{8,14} Initial attempts to apply MIS strategies only targeted patients with mild spinal deformities, including low pelvic tilt, low PI, or purely coronal curve corrections.^{2,17} Since the introduction of ACR, multiple studies have demonstrated an expansion in the ability of MIS techniques to successfully treat moderate to severe adult deformities with excellent SVA correction (± 5 mm SVA) and PI-LL correction ($\pm 10^\circ$), particularly when hyperlordotic cages are used.^{3,24,34,36} Further examination of segmental lordosis restoration showed that

a combination of ACR and varying degrees of PCOs can achieve greater correction of segmental lordosis, regional lordosis, and restoration of global sagittal balance.^{6,26,37}

Over the past 5 years, an increasing number of publications have described the role of ACR in adult deformity correction and its role in MIS correction of sagittal malalignment.^{1,9,11,21,25,38} Several studies have looked at the segmental change in lordosis in ACR with or without PCOs. Depending on the extent of adjacent posterior column resection, varying degrees of segmental correction can be achieved with ALL release and hyperlordotic cages. The

FIG. 5. Grade 3 and 4 ACR: ALL release with hyperlordotic cage and pedicle subtraction osteotomies. **A and B:** Lateral (A) and posterior (B) illustrations of the construct showing release of the ALL and a posterior pedicle subtraction osteotomy across the inferior vertebral body below the level of the ALL release. **C:** Additional lordosis can be achieved through a grade 4 ACR where a higher Schwab modifier includes a pedicle subtraction osteotomy through the disc space and vertebral body 2 levels distal to the interbody. **D–G:** Anteroposterior (D and E) lateral (F and G) standing radiographs demonstrating a lateral T10–ilium revision construct where a lateral grade 3 ACR was performed at L3–4 to correct a focal kyphotic deformity. Panels A–C used with permission from Barrow Neurological Institute.

greatest effect on the amount of segmental lordosis change is the severity of preoperative segmental kyphosis, the size of the cage used with ALL release (20° or 30°), and the amount of posterior column resection. However, various forms of confusing and inaccurate osteotomy language have been ineffectively used when describing radiographic outcomes in the literature. Thus, a unified nomenclature is needed to accurately classify ACR and standardize its description in the literature. Without a consistent and anatomically based classification system, the analysis of outcomes and comparison of results through a common language among surgeons treating deformities is not feasible.

The proposed ACR classification is simple, reliable, practical, and easy to adopt. The gradations of ACR are organized in progression of surgical complexity and degree of spinal destabilization and integrate with the well-established and reliable Schwab osteotomy classification.²⁷ Grades A–2 are “workhorse” techniques, typically applied in flexible or stiff spinal segments. Grades 3–5 are extensions of 3-column osteotomies and are best reserved for fixed/rigid deformities. Increasing degrees of segmental lordosis can be achieved with each increasing grade. The reported incremental segmental lordosis corrections are not, by any means, an exact definitive scale and should

FIG. 6. Grade 5 ACR: ALL release with vertebral body resection. **A:** Lateral illustration of the construct showing release of the ALL with vertebrectomy of the inferior body. The degree of vertebrectomy can vary from a complete to partial corpectomy in both height and width to accommodate different implant sizes or to preserve bony structures for fixation. **B–E:** Anterior-posterior (B and C) and lateral (D and E) standing radiographs demonstrating a T10–ilium construct with a lateral grade 5 ACR at L2–4 to correct a focal kyphotic deformity caused by progressive osteomyelitis. The vertebrectomy involved most of the body, but preserved the pedicles for additional fixation points. Panel A used with permission from Barrow Neurological Institute.

only be used as a guide rather than a rule. Variations in degrees of sagittal correction may be impacted by the technical execution of the ACR. For example, the senior author (J.S.U.) typically performs the posterior osteotomies in lateral grade 1 or 2 ACR first in order to maximize the size of interbody placement. However, a smaller interbody cage could be placed first, and then the posterior osteotomies performed second, with in situ rod contouring used to maximize segmental lordosis.

Through lengthening of the anterior column to generate lordosis rather than shortening the posterior column, ACR represents a fundamentally different conceptual paradigm from posterior osteotomies for sagittal realignment. Previously, there have been no formal organizational systems that outline anterior column manipulation techniques in a systematic fashion for surgical planning and communication. Our classification system fills this need and encompasses ACR techniques not only by their anatomical basis, but also by their approach, allowing inclusion of both MIS and open strategies. In turn, ACR can be recognized as more than just an extension of lateral LIF, enabling comprehensive description of different means of manipulating the anterior column such as through anterior LIF¹⁶ and posterior approaches.³¹ The “approach” modifier, while not important for grades A–2, can become valuable in grades 3–5, especially in the management of highly complex deformities. Mild variations in technical execution of the various ACR grades can exist, but comparative analysis is still possible through a unified nomenclature.

Generalizability and Limitations

Any attempt to organize and classify a group of different techniques based on retrospective data comes with

an inherent selection bias. The ACR technique is slowly increasing in popularity, but we are currently limited to only 9 studies published since 2012 describing the various ACR grades, each with limited patient numbers and radiographic analysis. Furthermore, although our classification model is validated by “nearly perfect” intra- and interobserver reliability, its utility and likelihood of adaptation by spine surgeons remains unproved.

While the focus of this paper is purely on anatomical classification of osteotomy/release realignment techniques, it is vital to keep in mind the potential morbidity of these procedures, especially at the beginning of the learning curve. The complication rate of the ACR and Schwab grade 3–5 osteotomies has been reported to range from 18% to 47% and includes major vascular injury, bowel perforation, and neurological injuries.^{4,22,26,30} These procedures should be performed only by surgeons trained in treating complex deformities and only when indicated and surgically feasible.

Conclusions

The proposed comprehensive anatomical classification of ACR techniques provides a consistent and dependable description of the various anterior lengthening releases combined with the well-established and reliable posterior Schwab osteotomy classification performed in the field of spine deformity surgery. Results of the reliability study show a near-perfect intraobserver and interobserver reliability, validating this classification system as a simple, consistent, and reproducible tool. Its application in varying scales of deformity correction confirms the classification’s practicality. Adaptation and use of this classification sys-

tem will provide a common platform for spine surgeons to communicate effectively and facilitate further progress in the field of deformity correction.

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Disclosures

Dr. Uribe: consultant for NuVasive and Misonix, and direct stock ownership in NuVasive. Dr. Schwab: consultant for Zimmer Biomet, MSD, K2M, and NuVasive; direct stock ownership in Nemaris Inc.; speaking/teaching arrangements with Zimmer Biomet, MSD, K2M, and NuVasive; support of non-study-related clinical or research effort from DePuy, NuVasive, K2M, and Stryker (paid through ISSGF). Dr. Mundis: consultant for NuVasive, K2M, and Allosource; and patent holder with NuVasive and K2M. Dr. Hu: direct stock ownership in and intellectual property with NuVasive. Dr. Eastlack: consultant for NuVasive, Aesculap, Seaspine, Titan, K2M, and Alphatec; direct stock ownership in NuVasive, Seaspine, and Alphatec; ownership in Spine Innovation; patent holder with NuTech, Globus Medical, and Iviuty; and consultant for SI Bone. Dr. Berjano: consultant for NuVasive and Medacta and support of non-study-related clinical or research effort from DePuy Synthes, NuVasive, and K2M. Dr. Mummaneni: consultant for DePuy Spine, Globus, and Stryker; direct stock ownership in Spinicity/ISD; support of non-study-related clinical or research effort from ISSG and NREF; royalties from DePuy Spine, and Thieme Publishing, Springer Publishing; and honoraria from AO Spine.

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Conception and design: Uribe. Acquisition of data: Schwab, Mundis, Januszewski, Hu, Deviren, Eastlack, Berjano, Mummaneni. Analysis and interpretation of data: Uribe, Schwab, Mundis, Januszewski, Kanter, Okonkwo, Hu, Deviren, Eastlack. Drafting the article: Uribe, Xu, Januszewski, Kanter, Okonkwo, Mummaneni. Critically revising the article: Uribe, Schwab, Mundis, Xu, Kanter, Okonkwo, Deviren, Berjano, Mummaneni. Reviewed submitted version of manuscript: Uribe, Xu, Eastlack, Berjano, Mummaneni. Administrative/technical/material support: Xu.

Supplemental Information

Previous Presentations

An early version of this study was presented at Spine Summit 2018: 34th Annual Meeting of the Section on Disorders of the Spine and Peripheral Nerves, Orlando, FL, March 17, 2018.

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