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Cervical mismatch: the normative value of T1 slope minus cervical lordosis and its ability to predict ideal cervical lordosis

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OBJECTIVE Numerous studies have attempted to delineate the normative value for T1S−CL (T1 slope minus cervical lordosis) as a marker for both cervical deformity and a goal for correction similar to how PI-LL (pelvic incidence–lumbar lordosis) mismatch informs decision making in thoracolumbar adult spinal deformity (ASD). The goal of this study was to define the relationship between T1 slope (T1S) and cervical lordosis (CL).

METHODS This is a retrospective review of a prospective database. Surgical ASD cases were initially analyzed. Analysis across the sagittal parameters was performed. Linear regression analysis based on T1S was used to provide a clinically applicable equation to predict CL. Findings were validated using the postoperative alignment of the ASD patients. Further validation was then performed using a second, normative database. The range of normal alignment associated with horizontal gaze was derived from a multilinear regression on data from asymptomatic patients.

RESULTS A total of 103 patients (mean age 54.7 years) were included. Analysis revealed a strong correlation between T1S and C0–7 lordosis ($r = 0.886$), C2–7 lordosis ($r = 0.815$), and C0–2 lordosis ($r = 0.732$). There was no significant correlation between T1S and T1S−CL. Linear regression analysis revealed that T1S−CL assumed a constant value of 16.5° ($R^2 = 0.664$, standard error 2°). These findings were validated on the postoperative imaging (mean absolute error [MAE] 5.9°). The equation was then applied to the normative database (MAE 6.7° controlling for McGregor slope [MGS] between −5° and 15°). A multilinear regression between C2–7, T1S, and MGS demonstrated a range of T1S−CL between 14.5° and 26.5° was necessary to maintain horizontal gaze.

CONCLUSIONS Normative CL can be predicted via the formula $CL = T1S - 16.5° \pm 2°$. This implies a threshold of deformity and aids in providing a goal for surgical correction. Just as pelvic incidence (PI) can be used to determine the ideal LL, T1S can be used to predict ideal CL. This formula also implies that a kyphotic cervical alignment is to be expected for individuals with a $T1S < 16.5°$.

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KEYWORDS T1 slope; cervical lordosis; cervical mismatch; T1S−CL; sagittal alignment; deformity

ABBREVIATIONS ASD = adult spinal deformity; CBVA = chin-brow vertical angle; CL = cervical lordosis (C2–7 lordosis); C0 = occiput; cSVA = cervical SVA; HRQOL = health-related quality of life; LL = lumbar lordosis; MAE = mean absolute error; MGS = McGregor slope; PI = pelvic incidence; PT = pelvic tilt; RMSE = root mean square error; SVA = sagittal vertical axis; TIA = thoracic inlet angle; TK = thoracic kyphosis; T1S = T1 slope; T1S−CL = T1S minus CL.

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Much has been written on the relationship between patient-reported outcomes and sagittal alignment in thoracolumbar deformities.[5–8,12,17,18,23] Although simple equations were initially used to identify thoracolumbar deformities, more recently, patient-specific formulas have been developed to more specifically quantify each deformity.[10,22] However, cervical spine studies have yet to define a fundamental equation, let alone patient-specific descriptors, that both elucidate a deformity and suggest a nidus for correction.

The cervical sagittal vertical axis (cSVA) has been widely used to quantify the extent of a cervical deformity and to provide a framework for correction. It has been shown that, ideally, cSVA should be less than 4 cm[27] and that a larger cSVA leads to worse health-related quality of life (HRQOL) scores.[26] However, this value does not differentiate the driver of the deformity—whether a deformity originates in the cervical spine or the malalignment is secondary to a thoracolumbar deformity with cervical compensation.

Without a clear target, aside from cSVA, some surgeons aim to "restore" lordosis when operating on the cervical spine. The problem with this, however, is that there is no uniform normal cervical lordosis. Nearly 34% of asymptomatic subjects in one study were found to have a baseline cervical kyphosis, which indicates that cervical kyphosis can, in fact, be a normal physiological parameter.[19] Reliance on cSVA or simple cervical alignment parameters without a predicted ideal cervical lordosis (CL) makes cervical deformity correction difficult and less exact, leading to either residual deformity or the creation of iatrogenic deformity where there previously was none.

The T1 slope (T1S) is possibly the key to understanding cervical sagittal alignment.[21] Given its correlation with the thoracic inlet angle (TIA), thoracic kyphosis (TK), cSVA, CL, and T1S minus CL (T1S−CL), T1S appears to be the lone variable linking both the cervical and thoracolumbar spinopelvic parameters.[9,14,20,21,30] In addition, of all of the cervical parameters, T1S has the strongest correlation with the C2 plumbline.[16]

Despite the postulation by Iyer et al. that CL, T1S, and T1S−CL all correlate with HRQOL measures in patients with cervical deformity,[11] there is no validated measure to define the goals of cervical deformity correction. Just as the pelvic incidence (PI) is used to determine the ideal lumbar lordosis (LL), the T1S has been suggested as the driver of the cervical lordosis. This current study attempts to define cervical curvature in terms of the underlying T1S. This study hypothesizes that T1S−CL is an independent variable that can be used to determine an ideal CL given a specific T1S.

Methods

Patient Population

This retrospective analysis of prospectively collected data is based on 2 separate databases: a multicenter database of surgical adult spinal deformity (ASD) patients collected through the International Spine Study Group (ISSG) and an adult spine normative database that was used as a control. Inclusion criteria for the ISSG database included patients older than 18 years who underwent surgical intervention for documented thoracolumbar spinal deformity based on at least one of the following measures: coronal Cobb angle > 20°, sagittal vertical axis (SVA) > 5 cm, PT > 25°, or TK > 60°.

In addition, cervical spine data, including the McGregor slope (MGS; the angle between the line from the posterosuperior aspect of the hard palate to the caudal aspect of the opisthion and the horizontal), had to be available. The MGS has been validated as a surrogate measure for the chin-brow vertical angle (CBVA) when the CBVA is not visible on a radiograph. A range of MGS between −5° and 15° was correlated with low disability and thus assigned to be the "normal range."[16]

Inclusion criteria for this study, specifically, required that the patients in the ASD database had no previous cervical fusion and an MGS between −5° and 15° pre- and postoperatively.

The second database was composed of data from asymptomatic volunteers, prospectively collected at a single center after institutional review board approval. The subjects had to be at least 18 years old with no history of spinal surgery and no complaints involving the spine. Full-body coronal and sagittal low-dose radiographs (EOS imaging system) were obtained in all cases. Exclusion criteria included 1) a history of prior spine surgery; 2) a Cobb angle > 10°; 3) any remote history of back or neck pain that resulted in missed work, the use of narcotic pain medication, or a change in normal activities; 4) a history of any lower-extremity realignment surgery (arthroplasty, trauma requiring instrumentation); 5) a history of inflammatory arthritis, congenital anomalies, or a history of neuromuscular disease; 6) nonambulatory volunteers; and 7) pregnancy.

Radiographic Analysis and Data Collection

Basic demographic data including age, sex, and BMI were collected on all included subjects from both databases. Full-length, free-standing anteroposterior and lateral spine radiographs were analyzed using a dedicated and validated software system (SpineView, ENSAM ParisTech).[3] The cervical and cranial alignments of included subjects from both databases were evaluated via MGS, T1 slope (T1S, the angle between the superior endplate of T1 and the horizontal), C0–2 lordosis (with C0 indicating the occiput), C0–7 lordosis, C2–7 lordosis (CL), cSVA, and T1S−CL. In addition, the PI, pelvic tilt (PT), PI-LL, and sagittal vertical axis (SVA) were all measured. The first available postoperative radiograph, typically the 6-week postoperative radiograph, was used for the postoperative cervical measurements in the ASD database. Patients were also stratified based on their SRS-Schwab classification modifiers.

Statistical Analysis

Mean values, standard deviations, and ranges for demographic data were reported for both databases. The mean values of the sagittal alignment at baseline and postoperatively were described in the ASD population. A preoperative-to-postoperative analysis using a paired t-test was performed in order to investigate the mean change in alignment for each radiographic parameter. The sagittal alignment of the normative cohort was described using the same parameters.

Predictive Formula Development and Validation in the ASD Group

Pearson bivariate correlation analysis was performed between T1S and the cervical lordosis parameters, including the C0–2 lordosis, CL, cSVA, and T1S−CL, in the ASD operative database. Subsequently, a stepwise linear regression analysis was conducted in the ASD group to predict the CL using the T1S as the independent variable. Results of this the linear regression were analyzed and subsequently simplified to provide a clinically applicable equation to predict CL based on the underlying T1S. This simplified equation was then tested by comparing the actual ASD patients' postoperative CL with the predicted CL using the mean absolute error (MAE) and the root mean square error (RMSE).

Predictive Formula Validation in the Asymptomatic Group

Further validation of the predictive formula was done using data from the asymptomatic volunteers. The novel equation was used to predict CL based upon T1S. The predicted CL was then compared to the actual value using the MAE and RMSE. Stratification by value of the error between predicted value and actual value was performed and 2 groups were generated: subjects whose CL was well predicted (error −5° to 5°) and those that were significantly overpredicted (error < −5°) or underpredicted (error > 5°). An ANOVA test was performed to compare demographic data, spinopelvic parameters, and global alignment between these 3 groups.

This validation of the predictive formula was then repeated by retaining only asymptomatic subjects with a "normal" horizontal gaze (i.e., MGS between −5° and 15°).

Finally, a regression analysis on the entire asymptomatic population was carried out to predict CL based on T1S and MGS. This equation was then solved in order to define the normative range of T1S−CL corresponding to published values of normal horizontal gaze.

Results

ASD Population

Of 837 patients in the prospective ASD database, 281 had sufficient data (including cranial parameters) available to be evaluated, and 103 of these patients met the inclusion criteria specific for this study. The mean age of these patients was 54.7 ± 16.6 years and their mean BMI was 25.3 ± 5.0; 90% were female.

The thoracolumbar alignment changed significantly between pre- and postoperative radiographs. There was no statistically significant difference in the cervical alignment parameters (Table 1). When the SRS-Schwab classification modifiers were applied, 30.1%, 21.4%, and 30.1% had "+" modifiers regarding the PT, PI-LL, and SVA, respectively; 21.4%, 28.2%, and 17.5% had "++" modifiers in each category.

In comparison to the preoperative radiographs, the postoperative T1S increased by more than 5° in 17.5% of patients, decreased by more than 5° in 35.0% of patients, and remained within 5° of baseline in 47.6% of patients. Similarly, in comparison to the preoperative radiographs, the CL increased by more than 5° in 28.2%, decreased by more than 5° in 32.0%, and stayed within 5° of baseline in 39.8% of patients. Of note, there was a strong positive correlation between the preoperative to postoperative change in CL, and the preoperative to postoperative change in T1S ($r = 0.659$, $p < 0.001$), demonstrating that these 2 parameters were moving in the same direction following the thoracolumbar correction.

TABLE 1. Preoperative and postoperative thoracolumbar and cervical spine sagittal parameters in the ASD population

Measurement	Preop	Postop	p Value
PI	54.5° ± 12.4°		
PT	21.4° ± 11.2°	19.0° ± 9.9°	0.003
PI-LL	8.7° ± 20.7°	0.3° ± 14.2°	<0.001
SVA	37 ± 56 mm	13 ± 52 mm	<0.001
T4–12 kyphosis	−36.1° ± 18.5°	−40.7° ± 14°	0.003
T1S	28.1° ± 13.3°	29.4° ± 10.6°	0.084
cSVA	27 ± 12 mm	30 ± 13 mm	0.028
C2–7 lordosis	8.8° ± 14.7°	8.8° ± 12.6°	0.999
C0–2 lordosis	15.1° ± 9.3°	16.3° ± 8.8°	0.380

The most proximal upper instrumented vertebrae (UIV) included was T2. This allowed for a fully mobile cervical spine to compensate for changes in T1S. The most common UIV in this cohort were T10 (27.2%), T3 (18.4%), T4 (15.5%), T2 (9.7%), and T11 (8.7%).

Asymptomatic Population

The normative database included 119 subjects. The mean age of this normative group was 50.8 ± 17.0 years, the mean BMI was 28.0 ± 6.0, and 68% of the subjects were female. The PI, PT, PI-LL, and SVA in this normative database were 52.0° ± 11.43°, 14.0° ± 7.7°, −6.1° ± 12.5°, and −9° ± 45°, respectively. The mean T1S was 26.5° ± 9.5°, with a corresponding CL of 5.4° ± 12.7°.

ASD Population Analysis

Correlation analysis between T1S and the cervical lordosis parameters revealed a strong correlation between T1S and both C0–7 lordosis ($r = 0.886$) and C2–7 lordosis ($r = 0.815$). A strong correlation also existed between T1S−CL and C0–2 lordosis ($r = 0.732$). A moderate correlation existed between T1S and cSVA ($r = 0.470$). There was no correlation between T1S and T1S−CL ($r = 0.153$, $p = 0.124$), implying that T1S−CL was independent of the value of T1S.

Linear regression analysis across the preoperative alignment parameters using T1S as the independent variable demonstrated a very strong association between T1S and CL ($R^2 = 0.664$; $p < 0.001$) and led to the following equation: $CL = -16.46 + 0.901 \times T1S$. Of note, a negative value is assumed to be kyphotic in this dataset. Analysis of the beta coefficients demonstrated that a nearly 1:1 relationship exists between T1S and CL (beta = 0.901). This implied that there was a significant constant mismatch between T1S and CL of 16.5° ($p < 0.001$). To increase the clinical applicability, the resultant equation was simplified to CL = T1S − 16.5°.

Validation of this equation utilizing the postoperative ASD database returned a mean error of 1.5° ± 7.7° with a mean absolute error of 5.9°. The RMSE was 7.7°.

Asymptomatic Population Analysis

The second validation, based on the normative controls, revealed a mean error of −2° ± 9.5° with an MAE of 7.8° ± 5.8°. The RMSE was 9.7°. The CL of 40.3% of the 119 subjects in this normative database was well predicted (within ± 5°) with this formula. The cervical curvature was overestimated in 34.5% and underestimated in 25.2% of the subjects. Further analysis revealed no obvious difference in demographics, spinopelvic alignment, or global alignment between the groups. However, the CBVA and MGS were found to be significantly different between those patients whose CL was well predicted versus those whose CL was not well predicted. When retaining only subjects with a normal horizontal gaze (MGS between −5° and 15°), the mean error between actual and predicted CL was −1.7° ± 8.3°, with an MAE of 6.7° and an RMSE of 8.4°.

A regression analysis on the entire asymptomatic population between CL (dependent variable) and T1S and MGS (independent variables) led to an R^2 value of 0.585 ($p < 0.001$). Solving the resulting equation for an MGS ranging from −5° to 15° implied that a T1S−CL within the range of 14.5°–26.5° was necessary to maintain a horizontal gaze.

Discussion

Currently, there is no clear alignment goal for cervical deformity correction. Traditionally, increasing the lordosis, or, at the very least, maintaining sagittal alignment has been thought to improve outcomes in cervical surgeries.[29] In the lumbar spine, an ideal lordosis can be predicted based on the morphological PI.[6] No such guiding parameter has existed in the cervical spine.

The value of T1S−CL has been reported in numerous studies in the literature. Hyun et al. report T1S−Cl of 15.8° ± 9.4° in a postsurgical population with a threshold of normal of 26.1°.[9] In another study, Protopsaltis et al. determined that a T1S−CL greater than 17° implied a cervical deformity.[25] Oe et al. observed that outcome measures seemed to diminish as T1S−CL crossed a 20° threshold.[24] Diebo et al. examined the cervical alignment required to maintain horizontal gaze. In their review, a normal gaze was accompanied by a T1S−CL between 17.5° and 22.2°.[4]

This current study is the first to determine a value of T1S−CL based on a normal gaze and a mobile cervical spine and validate it on data from an asymptomatic population. This paper reports that T1S−CL value as 16.5° ± 2°. This seems to strongly correlate with previous work examining this parameter.

Unlike the PI, which is a morphological parameter, the T1S−CL appears to be a constant parameter independent of the T1S itself. In the lumbar spine, the mismatch between PI and LL can be expected to be greater than 10° in patients with a high PI and should ideally be closer to zero in patients with an average PI.[10,22] The mismatch between T1S and CL does not change in this way regardless of the underlying TK that sets the T1S (Fig. 1).

As previously mentioned, the T1S is the only cervical parameter that also correlates with the thoracolumbar spinopelvic parameters.[9,14,20,21,30] Use of the T1S to determine cervical lordosis links the cervical spine to the thoracolumbar spine. It was previously shown that high thoracic kyphosis leads to an elevated T1S.[9] This, in turn, is compensated for by an elevated CL which is commonly seen in patients with lumbar hypolordotic or thoracic hyperkyphotic deformities.[1,30]

In addition to providing an ideal cervical curvature, this formula reinforces the idea that a kyphotic cervical spine is not necessarily pathological. Previous reports have shown that kyphosis is present in up to 34% of asymptomatic people.[19] Based on this new formula, a person with a T1S less than 16.5° would be expected to have a kyphotic cervical spine. This is important when identifying an indication for surgery in an individual case or establishing a goal for correction. These situations present an obvious nidus for the creation of an iatrogenic deformity.

The correction of marked cervical deformities frequently requires the use of a 3-column osteotomy to restore an appropriate cSVA. C7 pedicle subtraction osteotomies were plagued by a high rate of C8 radiculopathy and weakness postoperatively.[28] For this reason, many surgeons now advocate upper thoracic osteotomies to correct cervical sagittal deformities. In these instances, no direct correction of subaxial cervical lordosis is provided. Rather, surgeons are relying on a change in T1S to restore balance to the spine. Given the constant relationship between T1S and cervical lordosis, decreasing the T1S via an osteotomy will allow for an overall smaller cervical lordosis to potentially become physiologically appropriate in a patient who would have required more lordosis prior to the osteotomy.

Frequently, the correction of thoracic or thoracolumbar deformities can lead to an alteration in T1S via a change in the underlying thoracic kyphosis. Surgeons should consider the flexibility of the cervical spine prior to thoracic/thoracolumbar deformity correction. Alteration of the T1S in the setting of a fixed cervical spine could potentially lead to a T1S−CL outside the norm and thus an impaired horizontal gaze. Future studies should both examine the changes in T1S that accompany thoracic/thoracolumbar deformity correction and attempt to formulate an equation used to predict an ideal T1S given a specific spinopelvic alignment—providing a link between the pelvis and the cervical spine.

There is a natural propensity to maintain a horizontal gaze. In the setting of ASD a mobile cervical spine is recruited as a compensatory mechanism to allow for a neutral gaze.[2,13,20] In this study, we found that a T1S−CL of 14.5° to 26.5° was necessary to maintain a normal line of site. Surgical correction that impairs the ability of the spine to compensate and achieve these parameters could potentially lead to increased postoperative disability due to the inability to maintain an appropriate gaze.

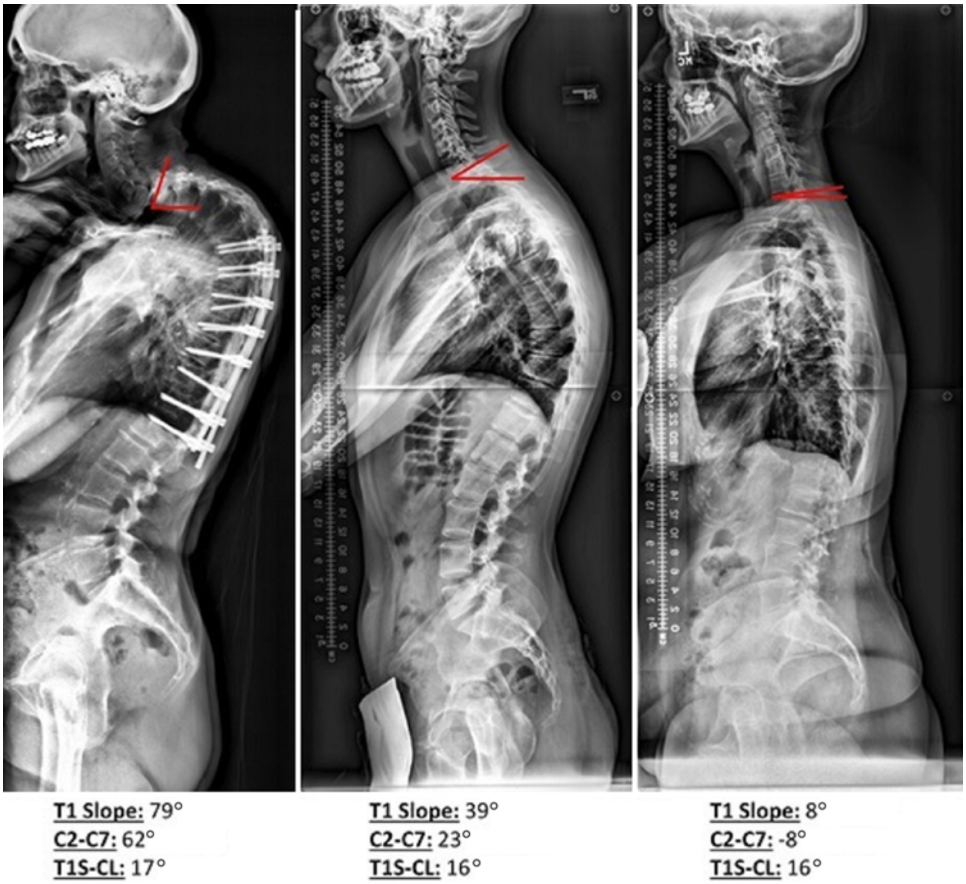

FIG. 1. Three examples of cases with markedly different T1 slopes. Despite the significant differences in T1 slope (T1S), the T1S–CL remains approximately the same, even if that requires a kyphotic cervical alignment. Figure is available in color online only.

Conclusions

In this study, there was no significant correlation between T1S and T1S–CL. This implies that cervical mismatch is independent of thoracic input and thus a constant. A normative CL for a given patient can be predicted by the following formula: $CL = T1S - 16.5° \pm 2°$. Not only does this formula possibly provide a threshold for cervical deformity, but it also implies a goal for surgical correction, whether that correction be attempted in the cervical spine to restore the cervical alignment or the upper thoracolumbar spine to correct the T1 slope. Future studies will look to prove this postulate by correlating subjective postoperative quality metrics with the correction of CL to fit this formula. It is also important to note that a neutral or kyphotic cervical spine is not necessarily pathological and would, in fact, be expected with a T1S less 16.5°.

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Disclosures

Dr. Shaffrey reports consultant relationships with Medtronic, NuVasive, Zimmer Biomet; direct stock ownership in NuVasive; and a patent-holder relationship with and receipt of royalties from Medtronic, NuVasive, and Zimmer Biomet. Dr. Mundis reports consultant relationships with NuVasive, K2M, and Allosource, and patent-holder relationships with NuVasive and K2M. Dr. Hostin reports a consultant relationship with DePuy Spine. Dr. Burton reports a consultant relationship with Allosource, receipt of clinical or research support for the present study from DePuy, and receipt of royalties from DePuy. Dr. Lenke reports a consultant relationship with Medtronic; prior consultant relationships with K2M and DePuy-Synthes Spine; receipt of royalties from K2M and Medtronic; receipt of grant support from DePuy-Synthes Spine, the Scoliosis Research Society (SRS), EOS, Setting Scoliosis Straight Foundation, and AOSpine; an expert witness relationship with Fox Rothschild, LLC (patent infringement case); receipt of royalties from Quality Medical Publishing; philanthropic research funding from Evans Family Donation and Fox Family Foundation; fellowship support from AOSpine; and reimbursement for airfare/hotel from Broadwater, Seattle Science Foundation, SRS, Stryker Spine, The Spinal Research Foundation, and AOSpine. Dr. Gupta reports a consultant relationship with, being on the Surgeon Advisory Board of, travel, and receipt of royalties from DePuy; being a personal stockholder with J&J and P&G; and payments from OMeGA and AOSpine to institution for fellowship support. Dr. Ames reports receipt of royalties from Stryker, Biomet Zimmer Spine, DePuy Synthes, NuVasive, Next Orthosurgical, K2M, and Medicrea; consulting relationships with DePuy Synthes, Medtronic, Stryker, Medicrea, K2M, and Biomet Zimmer; receipt of research support from Titan Spine, DePuy Synthes, and ISSG; receipt of grant funding from SRS; being on the executive committee of ISSG; and being director of Global Spinal Analytics. Dr. Klineberg reports consultant relationships with DePuy Synthes, Stryker, Springer, Trevena, and Allosource; receipt of honoraria from K2M; and receipt of honoraria and a fellowship grant from AOSpine. Dr. Bess reports a consultant relationship and patent-holder relationship with K2, receipt of clinical or research support for the present study from DePuy Spine, and receipt of support for non–study-related clinical or research efforts from K2, Medtronic, NuVasive, and Orthofix. Dr. Schwab reports direct stock ownership in Nemaris Inc.; consultant relationships with Zimmer Biomet, Medicrea, MSD, and K2M; speaking/teaching arrangements with Zimmer Biomet, MSD, and K2M; and support of non–study-related clinical or research efforts from DePuy, NuVasive, K2M, and Stryker (paid through

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Author Contributions

Conception and design: V Lafage, R Lafage. Acquisition of data: V Lafage, R Lafage, Kim, Shaffrey, Mundis, Hostin, Burton, Lenke, Gupta, Ames, Klineberg, Bess, Schwab. Analysis and interpretation of data: V Lafage, Staub, R Lafage. Drafting the article: Staub. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: V Lafage. Statistical analysis: V Lafage, R Lafage. Administrative/technical/material support: V Lafage, R Lafage. Study supervision: V Lafage.

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