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Modified Ondra's Formula to Predict Post-Op SVA after Lumbar PSO: A Preliminary Report Verified by Simulated Post-op Images Via Surgimap Software

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ABSTRACT

AIM: To introduce a new mathematical formula to predict sagittal vertical axis (SVA) changes after lumbar pedicle subtraction osteotomy (PSO).

MATERIAL and METHODS: This cross-sectional study included 43 patients. Lateral full spinal radiographs were exported from Picture Archiving and Communicating System and imported to Surgimap version 2.3.1.1 (Nemaris Inc, New York, NY) software for PSO simulation. Regression analysis was done on the first 16 cases to find a constant variable (K) in the proposed formula. PSOs of 15°, 20°,25°, 30°, and 35° were simulated at L3, L4, and L5 for each patient, and the simulated postoperative SVAs were compared to predict postoperative SVA. Paired T-Test, Spearman test, and analysis of variance were applied to analyze the results. The Statistical Package for the Social Sciences software (Version 24.0) was used for the statistical analysis.

RESULTS: Postoperative SVA was different in terms of PSO level and degree, with a mean of 74.87 ± 37.88, 66.12 ± 38.33, and 56.95 ± 38.53 at 15°; 61.76 ± 36.68, 50.13 ± 37.32, and 43.03 ± 36.67 at 20°; 48.61 ± 35.60, 39.13 ± 35.35, and 43.18 ± 31.56 at 25°; and 37.73 ± 33.78, 42.38 ± 28.76, and 44.81 ± 16.85 at 30° for L3, L4, and L5, respectively ($p<0.05$). The mean difference between the predicted SVA using the formula and the SVA simulated using Surgimap software was 2.37, 2.09, and 0.47 mm at L3, L4, and L5 levels, respectively. The mathematical formula was highly predictive for postoperative simulated SVA values in all three vertebral levels (L3–L5) ($p<0.05$). Additionally, a strong relationship was found between the vertebral level and the amount of SVA correction (Spearman correlation: 0.7–0.9).

CONCLUSION: The mathematical formula is an accurate predictor of postoperative SVA and is helpful in PSO surgical planning. However, future studies are recommended to verify its accuracy in a clinical setting.

KEYWORDS: Pedicle subtraction osteotomy, Sagittal balance, Sagittal vertical axis, Surgimap software

ABBREVIATIONS: ASD: Adult scoliotic deformity, **TH:** Truncal height, **SVA:** Sagittal vertical axix, **PSO:** Pedicle subtraction osteotomy, **PT:** Pelvic tilt, **PI:** Pelvic incidence, **HRQOL:** Health related quality of life, **PACS:** Picture archiving and communicating system, **ICC:** Intra class correlation coefficient, **SPSS:** Statistical package for the social sciences

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INTRODUCTION

The spine is known to have two main functions, namely energy-efficient weight-bearing and maintaining balance within the cone of equilibrium (7). Disturbances in the normal sagittal plane can worsen the health-related quality of life (HRQOL) and disability (3,8,9,10,23). Sagittal Vertical Alignment, defined as the distance of the C7 plumb line from the uppermost posterior point of S1, was developed to quantify this plane (27). Even the slightest positive deviations more than the normal range of 50 mm may lead to worsened HRQOL (8,9,14,18). Many studies have shown that the sagittal spinal imbalance correlates with the ongoing pain and disability in patients with adult scoliotic deformity (8,14,21,22).

Several types of corrective osteotomies have been introduced to restore sagittal balance (28). Pedicle subtraction osteotomy (PSO) and its new variants, such as corner osteotomy, are the procedures of choice for severe sagittal imbalance cases, which may correct SVA by adding up to 30°–35°to lumbar lordosis (LL) at a single level (5,6,11,12,15,26). One main concern is that PSO may exert unpredictable degrees of SVA corrections at different lumbar levels despite its popularity to correct sagittal balance. The result would lead to seemingly matched lumbopelvic indices with under-corrected sagittal balance, which may increase the risk of adjacent segment disease in the future.

Several preoperative planning schemes have already been proposed to decrease postoperative PSO-SVA discrepancy. The ideal preoperative planning should enable the surgeon correctly determine the degree and level of PSO to avoid postoperative PSOSVA discrepancy. Therefore, a few predictive formulas have been introduced, which are mostly based on individual parameters, such as pelvic incidence (PI), and compensatory indices, such as pelvic tilt (PT), sacral slope (SS), and T9 tilt (4,17,20). However, these formulas have mostly failed to help in real-life operations because changes in compensatory parameters, such as PT and T-9 tilt, cannot be intra-operatively controlled by the surgeon (13). Additionally, previous mathematical formulas were mostly unable to provide us with virtual postoperative images (19). The recent advancements in the virtual reconstruction of postoperative images obtained by computer software made virtual testing of such formulas before applying them to the clinical settings, now possible.

Surgimap spine (Numaris, Inc., New York, NY) is a radiologic software validated for spinopelvic parameter measurements with the ability to simulate PSO. The software was developed in 2008 by Numaris Inc, and since then, it has been constantly updated to include the most recent necessary spinopelvic parameters for preoperative planning. A few studies have been performed to validate the accuracy of this application. Atici et al. have questioned the accuracy of the software (2); however, another study performed by Akbar et al. has verified its accuracy (1). Merill et al. have also reported software-assisted precise measurements of PI, LL, and T1 pelvic angle (T1PA) following lumbar PSO, but not SVA (19).

This study aimed to provide the surgeons with a new mathematical formula, as a preoperative tool, to predict postoperative SVA changes after lumbar PSO.

Herein, we report our preliminary results employing Surgimap spine (Nemaris, New York, NY) to virtually test our new formula on simulated post-PSO images. Additionally, this study aimed to determine the predictive value of this formula to determine the level and number of lumbar PSO(s) to optimally correct SVA in patients with sagittal imbalance.

MATERIAL and METHODS

This is a longitudinal cohort of patients who are diagnosed with spinal deformities, which needed total standing spinal X-rays for further evaluation. All cases were adults (>21 years old at the time of radiography) with back pain and an obvious sagittal imbalance in standing, who required digital total spine X-rays. The study included patients from January 2020 to June 2020. Images were collected from one academic center that specialized in taking deformity X-rays. Exclusion criteria included unidentifiable X-ray landmarks (C2 vertebrae or bicoxofemoral axis) on plain films, severe coronal deformity (scoliosis), patient's refusal to participate in the study, congenital spinal deformities above L3 (hemivertebra, fused vertebra,etc.), clinical suspicion in favor of Parkinson's disease or neuromuscular disorders, and increased SVA in the presence of normal range PT. The study was approved by the institutional review board and the ethics committee to protect patients' privacy (IR.IAU.TMU.REC.1399.030).

All patients underwent AP and lateral digital total spinal radiography in a standard manner, which mandated maintaining a free-standing position with extended knees and pelvis and a clavicle position for arms. Radiographic images were extracted from the local Picture Archiving and Communicating System (PACS) in JPEG format and imported to Surgimap Version 2.3.0.1 (Nemaris Inc, New York, NY) software for further analysis.

Spinopelvic parameters were measured by the Surgimap software. After calibration, the SVA tool was used by marking the C-7 as the center and the very end of the posterior superior point on the S1 superior endplate. PT was measured by the angle formed between the line connecting the midpoint of the S1 superior endplate to the center of the bicoxofemoral axis and the vertical line drawn from the center of the bicoxofemoral axis (Figures 1 and 2A). With discordance between SVA and PT in favor of Parkinsonism or neuromuscular disorders, the patient was automatically excluded from the study. The patient's truncal height (TH), defined as the vertical distance between C-7center and S1 posterior superior point in our formula, was measured using the Line tool (Figures 1, 2A, and 3). Using the Wedge tool, PSO was simulated, placing the apex of the angle on the anterior cortex of the vertebra and the lower side parallel to the caudal endplate of the vertebra to the very bottom point of the pedicle on lateral film (Figures 1, 2, and 3). The angle was then set to 15°, the PSO was simulated on the vertebra, and the subsequent SVA was separately measured for L3, L4, or L5 vertebra. L1 and L2 PSOs were

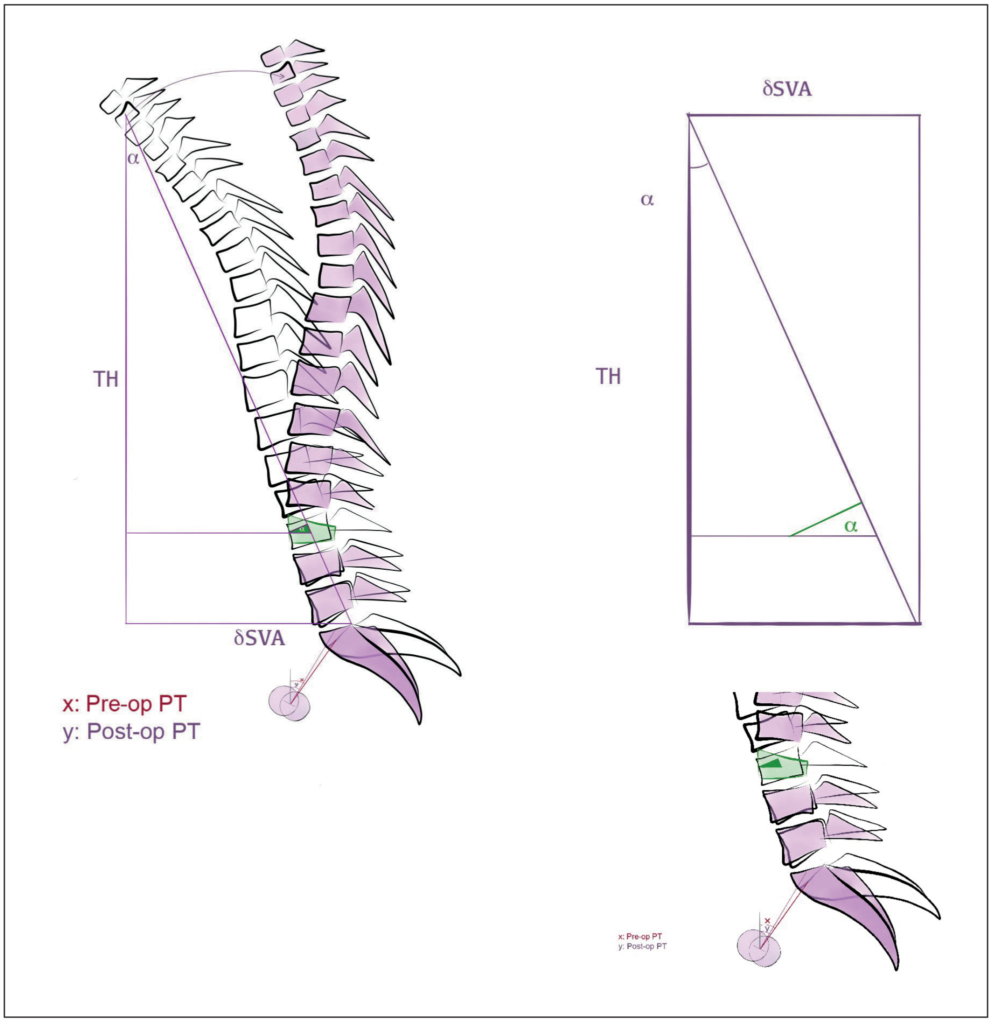

Figure 1: Schematic application of the trigonometric formula suggested by Ondra et al. (20) to predict post-pedicle subtraction osteotomy (PSO) sagittal vertical axis (SVA). This illustration depicts that PSO exerts a rotatory shift of the spinal column over the pelvis with the help of sacral anteversion, which causes pelvic tilt (PT) to get back to the normal range to correct the sagittal imbalance. As demonstrated here, this should not be interpreted as a simple linear SVA translation, but as a rotatory swing over the pelvis.

not considered in this study since they have little effect on LL and SVA correction and are rarely used by surgeons. The measurement was then sequentially repeated with PSO angles of 20°, 25°, 30°, and 35° until the SVA turned negative or the PSO angle exceeded beyond the uppermost point of the pedicle. The same work was conducted at L3, L4, and L5 levels, and virtual postoperative images were created for three lumbar levels (L3, L4, and L5), each undergoing five PSO degrees (15°, 20°, 25°, 30°, and 35°) (Figures 2 and 3). The SVA changes per PSO angle at each vertebral level were measured on the same image using the SVA tool. All measurements were separately performed bytwo of the authors (G.S and P.V) to maximize inter-and intra-observer reliabilities. The average of the two measurements by each observer was taken for data analysis.

A total of 43 patients were finally included in this study. Using Surgimap software, a total of 2,580 post-PSO virtual scans were created. For each image, SVA,TH, and PSO angles were measured using SVA, line, and wedge tools.

Generating the Mathematical Formula

We hypothesized a constant variable (*K*) to be added to Ondra's trigonometric formula for each lumbar level to attain a better estimation of post-op SVA and consider the role of uncontrollable pelvic parameters and rotatory nature of the sagittal correction. Therefore, the following formula was suggested to be verified in this study (Figure 1).

$$\Delta SVA = TH \times 0.017 \times PSO\ Angle^{\circ} \times K$$

Generating a Linear Regression Equation

We fractured the change of SVA of the first 16 consecutive cases by multiplication of height (Ht), a tangent of 1° (0.017), and the angle of PSO at each vertebral level (L3, L4, and L5) to calculate the constant variable (K) in our formula for the same patient and called the result K-3, K-4, and K-5 (Table I), thereby generating a regression equation, which was later tested by cases 17–43.

Validation of the Regression Equation

We applied the formerly developed equation to the remaining 27 cases for testing. Required variables, including primary SVA and TH, were measured, and the expected SVA was concluded by the formula for each lumbar level and angle. Secondary SVA that was simulated via Surgimap by applying

Table I: Constant Value of K for Each Vertebral Level (L3-L5)

	K-3	K-4	K-5
K	0.31	0.40	0.49

the PSO tool was also measured for the corresponding level and angle. Lastly, the difference between the expected SVA that was calculated by the formula and the secondary SVA that was simulated by Surgimap was used for statistical analysis.

Statistical Analysis

The data were statistically analyzed using Statistical Package for the Social Sciences software Version 24 (SPSS, Inc.). Expected SVA changes that were calculated using the formula and the simulated SVA by Surgimap were evaluated using the paired T-test. The significance value was considered 0.05. The Spearman test was used to find any relation between PSO level and SVA correction. Inter- and intra-observer reliability was measured using the Intra-Class Correlation Coefficient (ICC) test.

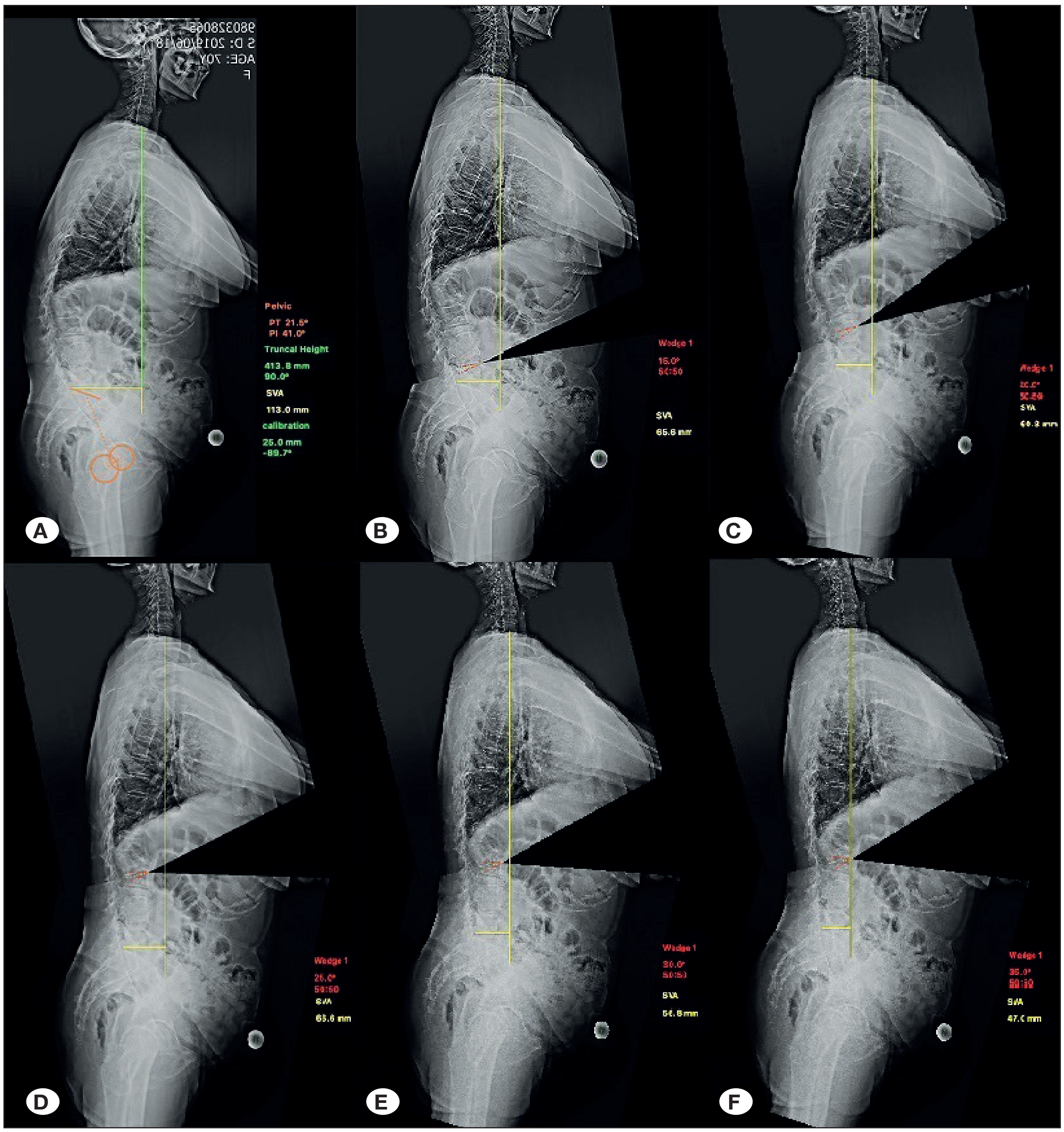

Figure 2: Step-by-step virtual post-PSO images were obtained by the Surgimap software in a patient with positive sagittal imbalance. **A)** Measurement of truncal height (TH), PT, pelvic incidence (PI), and SVA. **B)** Virtual post-PSO SVA with PSO angle of 15°. **C)** Virtual post-PSO SVA with PSO angle of 20°. **D)** Virtual post-PSO SVA with PSO angle of 25°. **E)** Virtual post-PSO SVA with PSO angle of 30°. **F)** Virtual post-PSO SVA with PSO angle of 35°.

RESULTS

A total of 43 patients met the inclusion criteria for the study. Using Surgimap software, a total of 2,580 simulated postoperative images were created by the two observers (G.S and P.V) and pre- and postoperative measurements, including PT, SVA, TH, and PSO angle, were recorded. The mean age of the patients was 64.34 years, ranging from 45 to 88 years (Figure 4). Male to female ratio was 47% (Figure 4). The preoperative SVA had a mean of 114.55 ± 44.5 mm. The mean predicted SVA was 74.87, 66.12, and 56.95 mm at a 15° angle, for L3, L4, and L5, respectively (Table II). These figures were calculated as 39.71, 39.47, and 24.2 mm at the final 35° angle, respectively (Table II). Simulated postoperative SVA has a mean of 37.59,

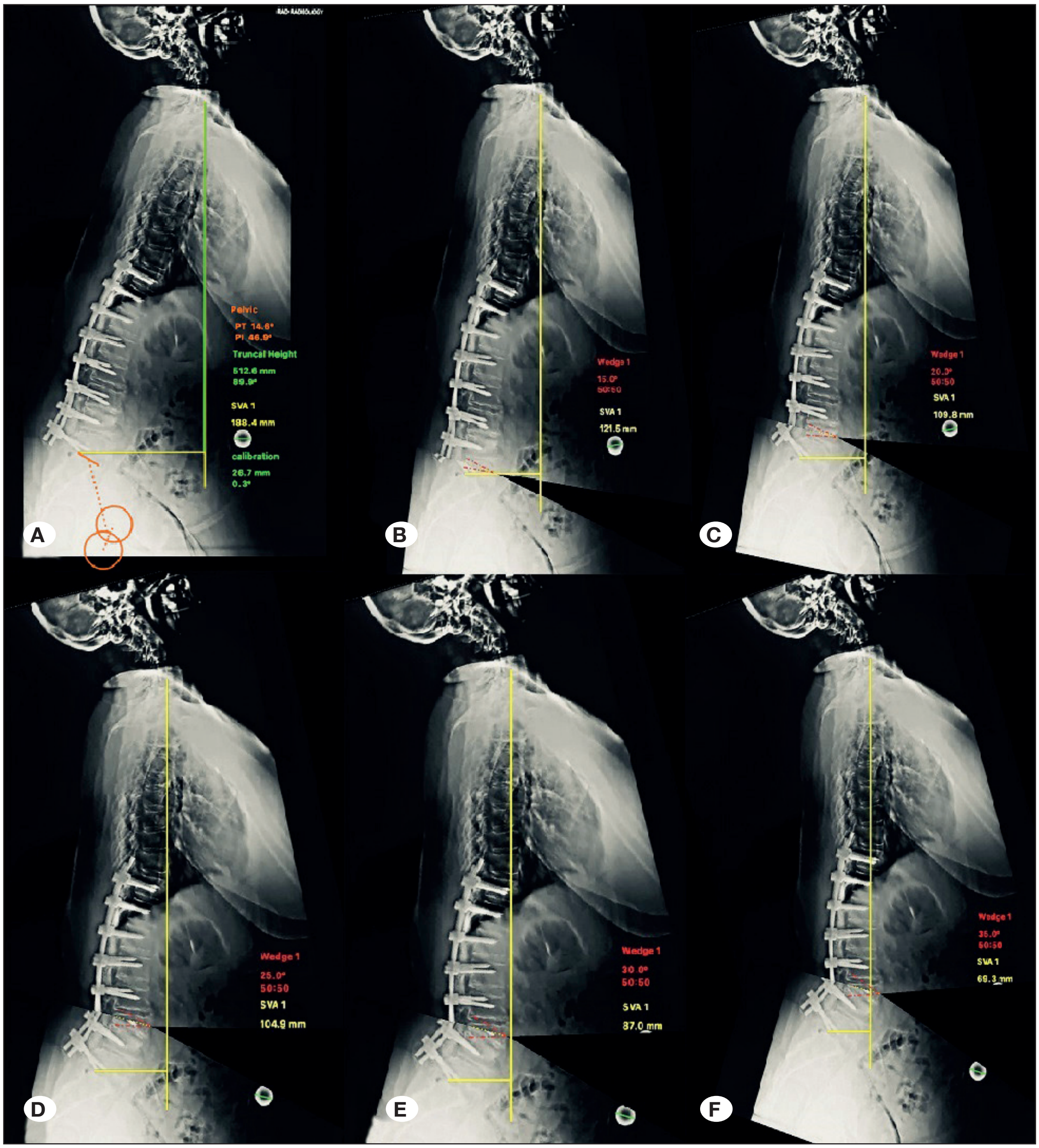

Figure 3: Preoperative planning to find the optimal PSO level in spinal revision surgery in a patient with positive sagittal imbalance after failed long segment spinal fusion. The formula suggested an L3 PSO angle of 35° to optimally correct the SVA, which has been confirmed by obtaining virtual post-PSO images using Surgimap. **A)** Preoperative measurements of SVA, TH, PT, and PI. **B)** Virtual post-PSO SVA with PSO angle of 15° at L5. **C)** Virtual post-PSO SVA with PSO angle of 20° at L4. **D)** Virtual post-PSO SVA with PSO angle of 25° at L3. **E)** Virtual post-PSO SVA with PSO angle of 30° at L3. **F)** Virtual post-PSO SVA with PSO angle of 35° at L3, which sounds the best PSO level to correct SVA.

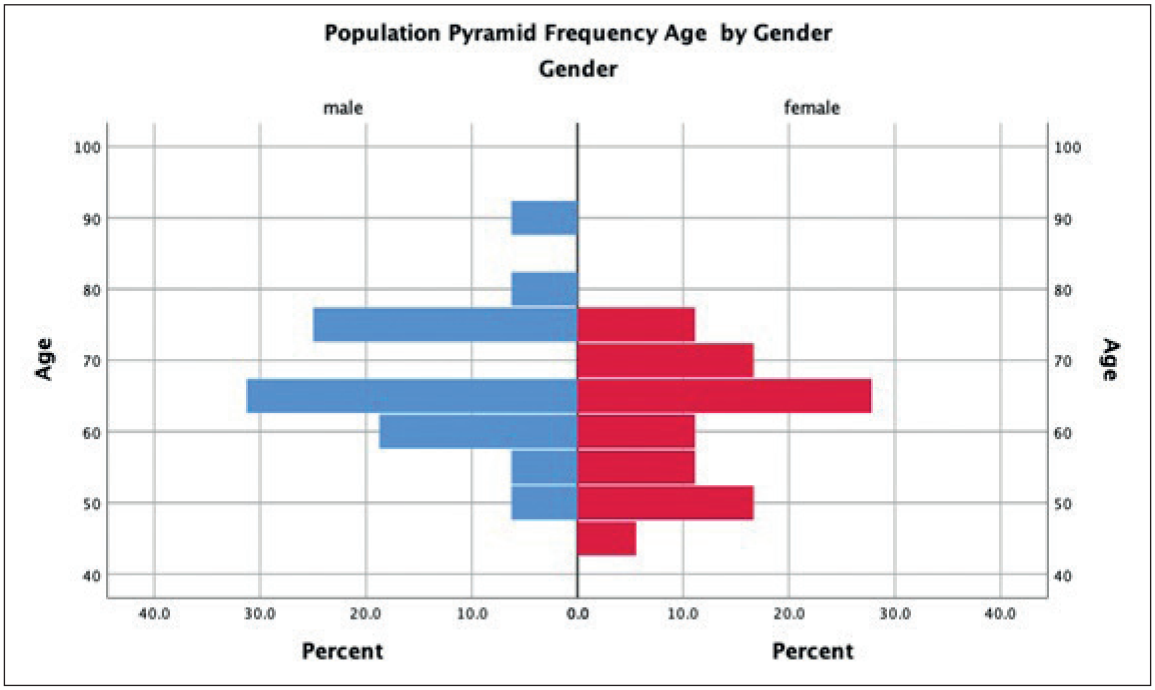

Figure 4: Age and gender distribution of patients.

Table II: Mean Predicted Post-op SVA per PSO Degree at Each Vertebral Level

	Post-op SVA L3	Post-op SVA L4	Post-op SVA L5
15°	74.87 ± 37.88	66.13 ± 38.33	56.95 ± 38.53
20°	61.76 ± 36.68	50.13 ± 37.32	43.03 ± 36.67
25°	48.61 ± 35.60	39.13 ± 35.35	43.18 ± 31.56
30°	37.73 ± 33.78	42.38 ± 28.76	44.81 ± 16.85
35°	39.71 ± 29.45	39.47 ± 20.58	24.2 ± 16.85

47.09, and 56.37 mm at 15° angle; 52.35, 64.43, and 74.20 mm at 20° angle; 66.27, 75.11, and 92.81 mm at 25° angle; and 78.25, 86.63, and 111.58 mm at 30° angle for L3, L4, and L5, respectively. Negative simulated SVA measurements after applying the wedge tool using the Surgimap software were excluded from the results. This occurred in 55% of patients when applying a PSO with 35°. The mean difference between the predicted SVA using the formula and the simulated SVA using the Surgimap software was 2.37, 2.09, and 0.47 mm at L3, L4, and L5 levels, respectively (Table III). The mathematical formula was found to be highly predictive for postoperative simulated SVA values in all three vertebral levels (L3, L4, and L5) ($p<0.05$). The PSO level has a strong relation with SVA correction (Spearman correlation=0.7–0.9).

A significant inter and intra-observer reliability was found using the ICC test ($p=0.000$).

DISCUSSION

A positive sagittal balance of >50 mm is an important cause of decreased HRQOL among patients with sagittal spinopelvic mal-alignment (8,14,15,18). PSO is an increasingly popular surgical corrective technique to restore sagittal imbalance among these patients (5,6,8,12,15,26). Postoperatively, a subgroup of patients, who underwent PSO to correct sagittal mal-alignment remain under-corrected or end up with poor surgical outcomes (24). Either under- or over-correction of SVA may lead to postoperative complications, e.g., pseudarthrosis, implant fracture or failure, rod breakage, and proximal or distal junctional kyphosis. Consequently, meticulous preoperative planning with the ability to create simulated postoperative images may give the surgeon a good idea of the appearance of the sagittal balance after the surgery.

The degree of SVA correction may differ in a single patient based on the PSO level and degree angle at each level. Upper lumbar levels exert a lower SVA correction as opposed to the lower lumbar levels (L4 and L5), which are known to create more LL.

In recent years, mathematical rule applications in spinal surgery have a growing interest. Accordingly, a few mathematical formulas have been suggested to help predict postoperative SVA after lumbar PSO (20,25). Although intriguing, such formulas have not gained enough popularity among spinal

Table III: A Comparison Between the Predicted and Simulated Post-op SVA per PSO Degree at Each Vertebral Level

	ΔSVA L3	Predicted ΔSVA L3	ΔSVA L4	Predicted ΔSVA L4	ΔSVA L5	Predicted ΔSVA L5
15°	38.35	35.05	47.1	45.23	56.27	55.41
20°	51.46	46.74	63.08	60.31	75.66	73.88
25°	64.61	58.43	79.56	75.39	95.65	92.36
30°	78.49	70.11	96.45	90.47	120.55	110.83
35°	92.53	81.80	116.28	105.26	141.16	128.94

surgeons in real-life surgeries. The spinal column shows opposite curvatures in adjacent areas, which may change in a compensatory manner, to correct nearby deformity and PSO rotates the spinal column over the pelvis, thus, mathematical formulas may help correlate the angular changes of PSO to linear alterations of SVA. Additionally, as PSO corrects the interplay between the spine and the pelvis by decreasing PT and pelvic retroversion, the role of pelvic compensatory mechanisms, such as PT, should also be considered in the suggested formula.

A multicenter survey by Smith et al. examined five common mathematical formulas to predict postoperative sagittal alignment (25) and revealed that the formulas, considering pelvic geometry, were more accurate in predicting postoperative SVA. Our study results also confirm that the accuracy of predicting postoperative SVA may be enhanced considering the role of pelvic parameters in such formulas.

Lafage et al. showed no relationship between PSO level and the SVA correction (15). However, some other reports suggest that the simple trigonometric calculations, considering osteotomy level and C7 plumb line, are poor predictors of SVA correction (29,30). The main criticism is that such a formula neglects the role of pelvic compensatory mechanisms. The results of our study showed a strong correlation between PSO level and SVA correction by introducing the role of compensatory mechanisms as the variable “K” in our suggested formula. This may provide some evidence that accurately predicting the ideal lumbar level and PSO angle is possible to achieve an optimal correction of the sagittal balance.

Some prior formulas only rely on fixed parameters, such as PI, and controllable factors, such as LL and thoracic Kyphosis (13,16). A multicenter study done in 2012 by Lafage et al. evaluated two spinopelvic alignment formulas that could predict postoperative SVA using parameters, such as maximal LL, thoracic kyphosis (TK), SVA, and PI (13). They found that the formulas were accurate in predicting both postoperative SVA and PT. Lafage et al. also believe that formulas employing pelvic parameters are more accurate to predict unsuccessful outcomes than successful outcomes and may be used to change the surgical plan by increasing the PSO angle in possible unsuccessful cases (13). The main drawback of such formulas is that the controllable factors of these formulas, i.e., LL and TK, cannot usually be accurately achieved during the surgery, providing us with a different result than predicted (19).

Our study revealed that the mean difference between the formula of predicted SVA and the postoperative SVA, simulated by Surgimap software, was 2.37 mm at L3, 2.09 at L4, and 0.47 at the L5 level. Compared to the formula evaluated by Lafage et al. with a 27 mm mean absolute error between the predicted and postoperative SVA (13), our suggested formula appears to be significantly more accurate in predicting post-op SVA.

The present study has some shortcomings, as well. First, the role of the introduced variable “K” needs to be clarified in future studies. This variable has been introduced in the present formula to consider the role of compensatory factors, such as PT, and rotatory motion of the spine over the pelvis, which was not considered by former trigonometric formulas; thus, future directions would clarify the possible factors that determine “K” for each patient and each lumbar level. Second, the TH has been considered as a constant number, in our formula, before and after PSO application. The pre- and post-PSO TH was not very different in our study using the Surgimap software; however, this needs to be sought in future clinical settings. Third, this preliminary study only evaluates three lumbar levels (L3, L4, and L5); thus, the predictive role of our formula needs to be verified for L1 and L2 PSO in the future.

Accurate preoperative planning in PSO surgeries helps decrease postoperative complications, such as pseudarthrosis, implant breakage, and proximal and distal junctional kyphosis. Therefore, a predictive formula with the potential to predict the desired PSO level and angle with minimal errors will help inoptimally correcting SVA and can be used as a preoperative tool in surgical planning. The proposed formula in this study indirectly considers the role of compensatory or uncontrollable variables, such as PT. Additionally, it could be used by the surgeons for comfortable preoperative planning due to its accuracy in predicting postoperative SVA in all three vertebral levels (L3, L4, and L5) compared to Surgimap simulated postoperative images. This formula is calculated and verified based on simulated operations by the Surgimap software; thus, further clinical studies with a large sample size are necessary to validate this formula in a clinical setting. Furthermore, the present formula can only predict the results of a single level osteotomy on SVA correction. Thus, further expanding the potencies of this formula is recommended to predict the outcome of multi-level lumbar osteotomies.

CONCLUSION

Mastering the techniques of realignment and preoperative planning are of crucial importance to achieve optimal results with PSO in deformity surgery. The present study showed the accuracy of a novel modified trigonometric formula to predict post-PSO SVA alterations based on the PSO level using the Surgimap software. This formula can be used as an adjunct preoperative tool for surgical planning in patients with sagittal mal-alignments; however, its true validity needs to be reassessed in clinical settings.

AUTHORSHIP CONTRIBUTION

Study conception and design: PV

Data collection: GS, ZV, PV

Analysis and interpretation of results: GS, ZV, PV

Draft manuscript preparation: GS, ZV, PV

All authors (GS, ZV, PV) reviewed the results and approved the final version of the manuscript.

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