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Original Article

# A novel system for accurate lumbar spine pedicle screw placement based on three-dimensional computed tomography reconstruction

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ABSTRACT

*Objectives:* The accuracy of pedicle screw placement strongly affects the outcome of spinal surgery and has mainly relied on the surgeons' experience. There is no simple, low-cost, and effective pedicle screw placement system to assist new spinal surgeons with less experience.

*Methods:* We designed a localization system with six parameters (starting point height [SP-H], starting point length [SP-L], transverse section angle, sagittal section angle [SSA], pedicle width [W] and height [H]) based on preoperative computed tomography reconstruction and combined it with the Roussouly classification to guide lumbar spine pedicle screw placement and analysed the change patterns of the six parameters in 50 participants.

*Results:* Based on the system, we confirmed that combining SP-H and SP-L can localize the entrance of the pedicle screw. Furthermore, we considered that SP-L and transverse section angle would be a new standard for determination of the transverse orientation of the pedicle screw. More importantly, the linear regression equations between H and W and SP-H and H were concealed. In addition, H and W can guide the appropriate selection of pedicle screw. Moreover, change patterns of SSA combined with the Roussouly classification indicate that SSA of L3 can be used as a benchmark to guide the establishment of sagittal alignment of the lumbar spine.

*Conclusions:* Understanding and applying the six-parameter localization system are essential for achieving accuracy in lumbar spine pedicle screw placement, and the system is a useful guide in the establishment of sagittal alignment.

*The translational potential of this article:* This study provides a new pedicle-screw placement system for accurate lumbar spine pedicle screw placement based on three-dimensional CT reconstruction, requiring six parameters to guide the system.

## Introduction

Accurate pedicle screw placement is essential in preventing spinal cord or nerve root iatrogenic injury [1,2]. Precise pedicle screw placement requires information regarding at least two important anatomical concepts: pedicle screw insertion point and route, including direction and depth. The establishment of an insertion point is the first and key step to perfect pedicle screw placement. Further, the insertion route in accordance with the axis of the pedicle screw can make maximum use of the pedicle coronal and sagittal diameter and is the safest route [3].

To localize the accurate insertion point of the pedicle screw, the main classic method is to find the anatomical structure of the crista lambdoidalis, transverse process root, and facet joint [4]. However, this localization method is difficult for inexperienced surgeons [5]. Furthermore, the risk of pedicle screw placement failure results in spinal deformities, degenerative hyperplasia of the posterior spinal structure, transverse process fractures, and other anatomical abnormalities owing to this localization method [6]. Therefore, the surgeon's experience is critical in these situations. Alternatively a guidance system, such as O-arm–based navigation, 3D fluoroscopy navigation, or a robotic guidance system, is needed to prevent placement failure [7–9]. However, these resources are limited because of their high cost and steep learning curve [10] and cannot be widely applied in all kinds of hospitals [11–13].

Fortunately, presently, computed tomography (CT) scan has become a routine preoperative examination for spinal surgery. Moreover, CT reconstruction is accurate, in which a three-dimensional (coronal,

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**Table 1**
Baseline of the participants.

| | | | | | |
|---|---|---|---|---|---|
| Age (yrs±SD) | 57.2 ± 15.6 | | Sex (male/female) | | 29/21 |
| Diagnosis ( numbar ) | LDH: 20 | LSS: 7 | LF: 7 | LS: 7 | Resurgery: 3 |
| | ST: 2 | LT: 1 | DP: 1 | LD: 1 | Sprain: 1 |
| Six parameters from L1-L5 ( Mean ± SD ) | | | | | |
| Parameters | L1 | L2 | L3 | L4 | L5 |
| SP-L (mm) | 18.7 ± 2.1 | 18.7 ± 1.8 | 20.1 ± 2.0 | 22.3 ± 2.0 | 26.7 ± 2.1 |
| SP-H (mm) | 14.1 ± 1.3 | 14.5 ± 1.3 | 14.2 ± 1.2 | 13.4 ± 1.4 | 13.3 ± 1.1 |
| TSA (°) | 12.4 ± 3.1 | 13.5 ± 3.0 | 15.6 ± 3.4 | 16.6 ± 3.7 | 22.7 ± 4.3 |
| SSA (°) | 5.3 ± 3.6 | 5.7 ± 3.3 | 3.1 ± 3.2 | −4.3 ± 6.2 | −16.0 ± 7.6 |
| W (mm) | 6.4 ± 1.8 | 6.6 ± 1.8 | 8.3 ± 2.1 | 10.1 ± 2.0 | 14.5 ± 2.2 |
| H (mm) | 14.1 ± 1.6 | 13.3 ± 1.6 | 12.8 ± 1.4 | 11.5 ± 1.5 | 10.6 ± 1.5 |
| Roussouly classification (number of participants) Type I: 19; Type II: 16; Type III: 11; Type IV: 4 | | | | | |

LDH = Lumbar Disc Herniation; LSS = Lumbar Spinal Stenosis; LF = Lumbar Fracture; LS = Lumbar Spondylolisthesis; ST= Spinal Tumour; LT = Lumbar Tuberculosis; DP = Discogenic Pain; LD = Lumbar Degeneration; SP-L = starting point length; SP-H = starting point height; TSA = transverse section angle; SSA, sagittal section angle; W, pedicle width.

sagittal, and cross-sectional) surface can be easily obtained at any angle to meet the requirements of personalized measurement [14,15]. We hope to establish a new pedicle screw placement system by preoperative CT scan and reconstruction, which has the advantages of individualized application, high accuracy, and easy identification.

## Materials and methods

### *Study participants*

Fifty patients (29 men and 21 women) with different lumbar spine diseases were enrolled in the study. The baseline characteristics of the participants are shown in Table 1. The inclusion criteria were performance of supine CT scan (Philips ICT) of the lumbar spine and the image data analysis in the Image Clinical Application and Platform. Patients with deformity or degeneration of the lumbar spine because of spinal tumour, infection, lumbar spondylolisthesis, and trauma were excluded. This study was approved by the institutional ethics review board. Written informed consent was obtained from each patient.

### *Imaging measurement*

We defined the axis of the pedicle as the intersection line of the equally divided transverse and vertical planes of the pedicle. The intersection point of the axis on the cortex of the posterior end of the pedicle is the starting point (SP). We used the SP as the best entry point of the pedicle screw and the axis of pedicle as the best insertion route.

There were six parameters measured based on CT reconstruction from each included patient (Fig. 1). Pedicle width (W) was the narrowest width of the pedicle in the equally divided transverse plane, which is perpendicular to the axis of the pedicle. Pedicle height (H) was the shortest height of the pedicle in the equally divided vertical plane, which is perpendicular to the axis of the pedicle. SP length (SP-L) was the distance from the SP to midline of the spinous process. SP height (SP–H) was the vertical distance from the vertex of the upper facet joint to the horizontal plane of the SP on the coronal plane. Transverse section angle (TSA) was the angle of the axis and middle line on the transverse plane. Sagittal section angle (SSA) was the angle of the axis and horizontal line on the sagittal plane. Both pedicles were measured. We analysed changes in all six parameters from L1 to L5 and the correlation between each of them.

In order to reveal the change pattern of SSA, the patients were divided into four groups from Type I to Type IV based on the Roussouly classification [16]. The classification was determined by sagittal CT reconstruction of the lumbar spine in the supine position. We analysed the changes in different lumbar types from different segments.

In addition, our system was based on CT scan, which allowed us to obtain accurate measurement data for the pedicle with abnormal anatomical structure such as deformity or degeneration. Software measurement can reduce errors so that the accuracy of linear data reaches 0.1 mm and the angle is equivalent to 1°.

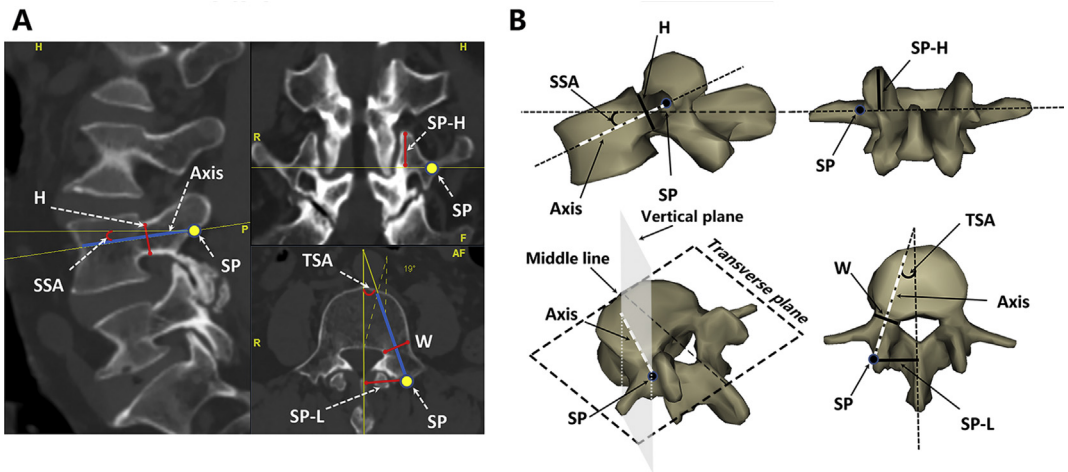


**Figure 1.** The imaging measurement of the six parameters. (A) A CT scan from one of the participants. The left picture is the sagittal section across the SP of L3 left pedicle. The right upper picture is the coronal section across the SP of L3 left pedicle. The right lower picture is the transverse plane across the SP of L3 left pedicle. (B) Schema chart of 3D reconstruction from the CT scan.

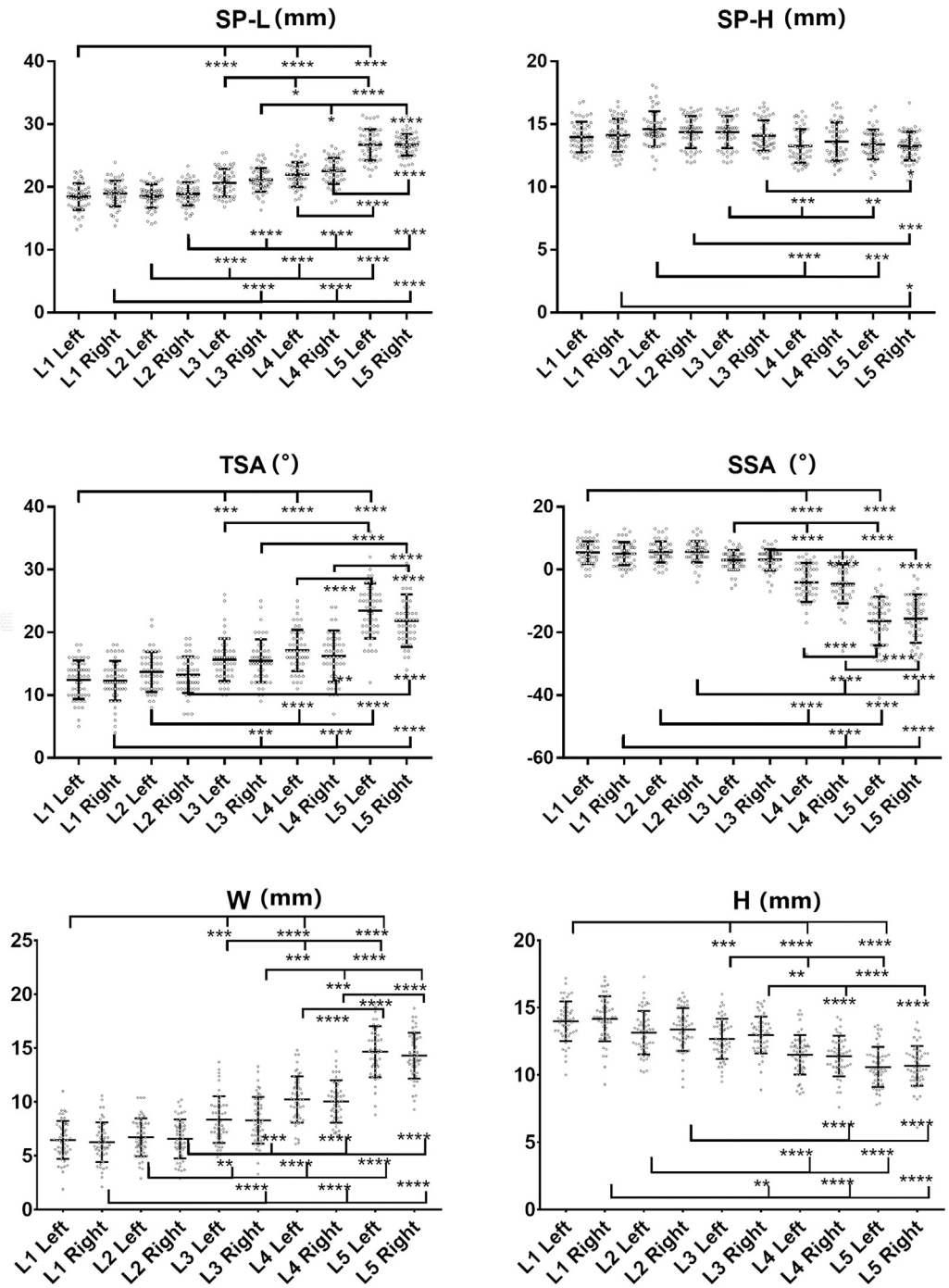


**Figure 2.** Scatter plot shows the changes of the six parameters from L1 to L5. Data are presented as the mean ± S.D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$, **** indicates $p < 0.0001$.

*Statistical analysis*

All parameters are measured twice by the same observer on two different occasions and once by another observer to determine the intraobserver and interobserver reliability, and the reliability was evaluated by intraclass correlation coefficients. The reliability of intraobserver and interobserver measurements was consistent if the ICC was between 0.82 and 0.98. Therefore, measurements obtained by one observer are used in the analysis.

The chi-square test and marched or unmatched t-test were used to evaluate the difference between the two groups. Pearson's correlation coefficient (r) was used to test the correlation between variables. The statistical significance was set at a P-value <0.05. The correlation coefficient was considered clinically statistically significant only when $r \geq 0.3$. All data were analysed by SPSS version 19 (SPSS, Chicago, IL).

## Results

*Change in the six parameters from L1 to L5*

SP-L, TSA, and W significantly and gradually increased from L1 to L5. SP-H, SSA, and H significantly and gradually decreased from L1 to L5 (Fig. 2). In all six parameters, both sides of the pedicles from the same lumbar segment did not show significant difference.

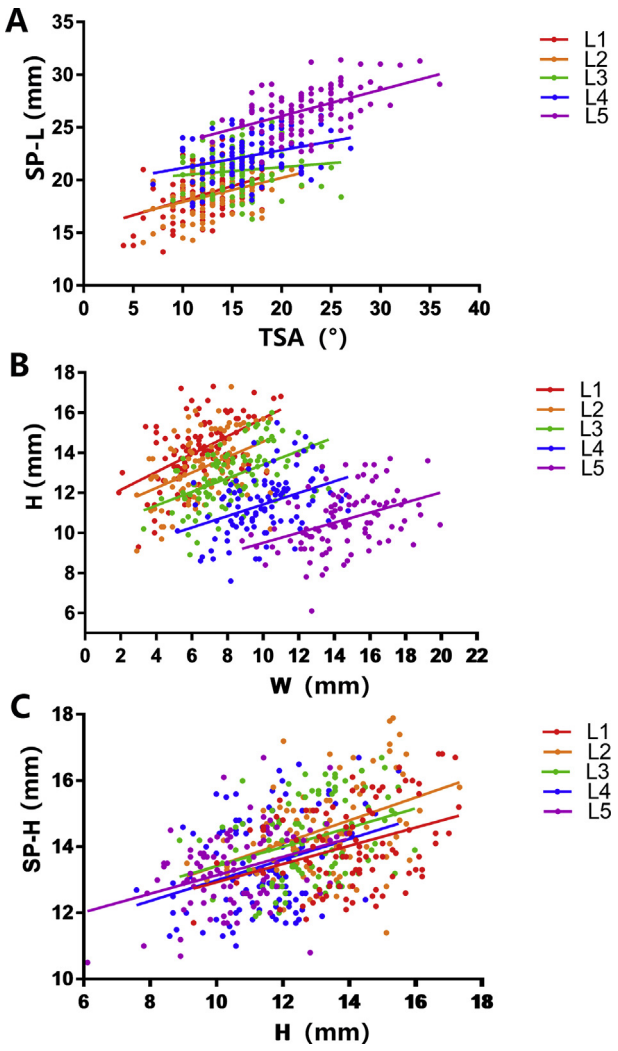


**Figure 3.** The linear regression between TSA and SP-L, W and H, H and SP-H. (A) The linear regression between TSA and SP-L. (B) The linear regression between W and H. (C) The linear regression between H and SP-H. SP-H, starting point height; SP-L, starting point length; TSA, transverse section angle; W, pedicle width; H, height.

*Linear correlation between SP-L and TSA*

Except in L3, there was a positive correlation between SP-L and TSA in all other lumbar segments (Fig. 3A), and the linear Pearson's correlation coefficient between SP-L and TSA was the highest in L5 (Table 2). Therefore, for a segment other than L3, the larger the TSA, the more externally deviated the SP; otherwise, the smaller the TSA, the more internally deviated SP will be. However, the slope and Y-intercept did not show significant difference from L1 to L5.

*Linear correlation between H and W*

There was a positive correlation between H and W in all lumbar segments (Fig. 3B). From L1 to L5, the slope and Y-intercept gradually and significantly decreased (Table 2). Indicating that the increase in W had less effect on the increase in H, from L1 to L5, the cross-sectional shape of the pedicles changed from an ellipse with H as the long axis to an ellipse with W as the long axis.

*Linear correlation between SP-H and H*

There is a linear correlation between SP-H and H, and the L1–L5 correlation equation is almost the same (Fig. 3C). The reason for the slight changes in slope and Y-intercept is the SSA change in the vertebra. With the correction of the SSA effect, we obtain the closest equation: $Y = 0.3 * X + 10$ (Table 2). SP-H can be obtained from H, which is usually measured in the clinic by substituting H into the equation, thus eliminating repeated clinical measurements. H can also be easily obtained by the equation presented in Table 2 by measuring W because W is a more common parameter used in clinical practice.

*Relationship between SSA and the Roussouly classification*

In the same segment, there was no significant difference between the left and right SSAs, and there was no significant difference after dividing the participants into Type I to Type IV subgroups.

In L1, SSA gradually increased from Type I to Type IV. Except for Type I with Type II and Type III with Type IV, all subgroups showed significant difference. In L2, SSA gradually increased from Type I to Type IV. Type III and Type IV significantly increased compared with Type I. In L3, from Type I to Type IV, all SSAs showed no significant difference. In L4, SSA significantly decreased from Type I to Type IV. Only Type II showed no significant difference compared with Type III, and the rest showed significant differences. In L5, SSA significantly decreased from Type I to Type IV, and there was a significant difference between the groups (Fig. 4A).

In a further intensive study, we found that there was no significant difference in the SSA of L3 in different lumbar types. The SSA of L3 is 3.1 ± 3.2. Moreover, we obtained the difference from L1-L5 to L3 (Supplementary Table).

Based on L3, SSAs from L1 and L2 of each type were not significantly different from L3. The mean difference in SSA between L4 and L5 with L3

**Table 2**
Linear correlation between SP-L and TSA, H and W, SP-H, and H.

| Linear correlation | Segment | Equation | R | Slope SEM | Y-intercept SEM | Slope P |
|---|---|---|---|---|---|---|
| Y=SP-L | L1 | Y = 0.2765*X + 15.3 | 0.4141 | 0.06138 | 0.7821 | <0.0001 |
| X = TSA | L2 | Y = 0.2293*X + 15.63 | 0.3770 | 0.05693 | 0.7859 | 0.0001 |
| | L3 | Y = 0.07557*X + 19.73 | 0.1243 | 0.06091 | 0.9697 | 0.2177 |
| | L4 | Y = 0.1685*X + 19.46 | 0.3094 | 0.05233 | 0.8934 | 0.0017 |
| | L5 | Y = 0.2486*X + 21.1 | 0.5094 | 0.04242 | 0.9782 | <0.0001 |
| Y=H | L1 | Y = 0.4458*X + 11.25 | 0.5100 | 0.07596 | 0.502 | <0.0001 |
| X = W | L2 | Y = 0.3857*X + 10.7 | 0.4295 | 0.08191 | 0.5633 | <0.0001 |
| | L3 | Y = 0.3395*X + 10 | 0.5104 | 0.05779 | 0.4967 | <0.0001 |
| | L4 | Y = 0.2877*X + 8.536 | 0.4005 | 0.06649 | 0.6877 | <0.0001 |
| | L5 | Y = 0.2521*X + 6.984 | 0.3847 | 0.06111 | 0.8952 | <0.0001 |
| Y=SP-H | L1 | Y = 0.2751*X + 10.18 | 0.3447 | 0.07571 | 1.073 | 0.0004 |
| X = H | L2 | Y = 0.3464*X + 9.957 | 0.3685 | 0.0883 | 1.18 | 0.0002 |
| | L3 | Y = 0.2903*X + 10.51 | 0.3351 | 0.08244 | 1.064 | <0.0001 |
| | L4 | Y = 0.3118*X + 9.869 | 0.3209 | 0.09293 | 1.073 | <0.0001 |
| | L5 | Y = 0.2798*X + 10.35 | 0.3582 | 0.07367 | 0.7908 | 0.0003 |

Slope P indicates slope is significantly nonzero. SP-H, starting point height; SP-L = starting point length; TSA = transverse section angle; W, pedicle width.

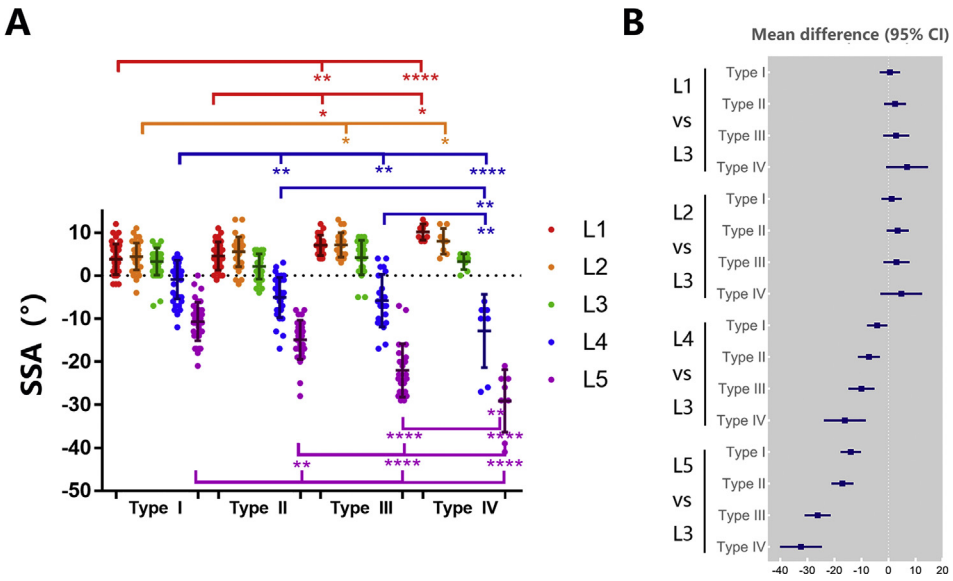


**Figure 4.** Relationship between SSA and Roussouly classification. (A) Scatter plot shows the changes of SSA in different lumbar type from Type I to Type IV. (B) Forest plot shows the mean difference with 95% confidence interval (CI) between L3 and all the other segments. Data are presented as the mean ± S.D. * indicates $p < 0.05$, ** indicates $p < 0.01$, *** indicates $p < 0.001$, **** indicates $p < 0.0001$. SSA, sagittal section angle.

was negative, and there was a significant difference (Fig. 4B). It indicated that lumbar type from the Roussouly classification determines the change in SSA. Applying L3 as the benchmark, the absolute mean difference between Type I and Type II was smaller than that between Type III and Type IV. Particularly, the changes in SSA from L1 to L5 was greater from Type I to Type IV, among which SSA from L3 had the least change and can be used as a benchmark.

## Discussion

In this study, we focused on the shape of the pedicle and used six parameters based on CT scan to establish a coordinate system to guide lumbar spine pedicle screw placement. First, we used SP-L and SP-H in this system to replace the inaccurate but traditional crista lambdoidalis method as the SP for placement of the pedicle [4]. Unlike SP-L, which has gained much attention and has been the subject of extensive study [17], SP-H was first put forward in this study. Further, there is no literature report that has combined these two parameters to determine the insertion point of the pedicle. We have already used SP-H in clinical practice and found that it can be easily measured with CT reconstruction preoperatively and during transforaminal lumbar interbody fusion surgery. The transverse process is also a common anatomical site to determine the SP. However, compared to the facet joint, it is more difficult to precisely measure the distance of SP from the upper or lower border of the transverse process in CT scan because the width of the transverse process is remarkably small and would easily affect the accuracy [18,19].

Furthermore, considering that most preoperative preparations for pedicle screw placement only focus on the narrowest W to choose the appropriate width of the pedicle screw, it is obvious that W is often measured clinically [20]. In this study, we find that W has a linear correlation with pedicle's narrowest H which can be depicted by an equation. We can incorporate the most common clinical pedicle data W into the equation, obtain H, and further guide the choice of pedicle screw size. Simultaneously, we also observed a correlation between H and SP-H in this study. While collecting the H data, we can also obtain SP-H to determine the entry point of the pedicle screw during surgery. Therefore, by a simple CT scan, we can obtain W. Through substitution in the equation, the more instructive parameter H and SP-H can be obtained for guidance of intraoperative pedicle screw placement, eliminating the inconvenience of CT reconstruction and repeated measurements.

In addition, the reason for the correlation between W, H, and SP-H can be easily explained by examining the development of the pedicle. As the pedicle and facet joint develop from the same cartilage germinal centre after the eighth embryonic week, the primary ossification centre of each lumbar pedicle grows almost at the same time and the final pedicle fusion timing is delayed from L1 to L5 until 10 years of age, which explains the regular shape change of the pedicle from L1 to L5 and the unaltered correlation between H and SP-H. In order to provide an explanation for this phenomenon, the second primary ossification centre and the mechanical load should also be considered [21–23]. However, this requires more experiments and is not the focus of this study.

After confirming the SP of the pedicle screw by SP-L and SP-H and choosing the appropriate width of the pedicle screw by W and H, we consider that the angle of pedicle screw placement can be guided by TSA and SSA. TSA can be accurately measured by a CT scan, which is also a common and necessary parameter in surgical planning [24]. Moreover, we found that TSA is related to the sequence of the vertebra. The lower the vertebral body, the larger is the TSA. At the same time, SP-L will be larger. We found a positive correlation between SP-L and TSA, which may be explained as a right triangle effect. SP-L can be considered as the right-angle edge and TSA as the opposite angle. The larger the TSA, the longer is the SP-L. For this reason, TSA and SP-L would become the parameters to confirm the transverse orientation of the pedicle screw.

More importantly, we considered SSA to be one of the other essential parameters. SSA is associated with sequence of the vertebra. If the vertebra is low, the SSA will change from positive to negative and may reach −40°. However, the subgroup that displayed the greatest variation was Type IV, and this can most probably be attributed to the increased incidence of lumbar lordosis in this group [16]. Meanwhile, the SSA of Type I changed only slightly from L1 to L5 because of the low incidence of lumbar lordosis in the group. Furthermore, we found that SSA of L3 remained the same in all subgroups, which was applied as the benchmark of SSA. Based on this benchmark, we can forecast the exact SSA in other segments with consideration of the different lumbar types. Furthermore, SSA could be our guide to recover the sagittal alignment of the lumbar spine by applying the marched pedicle screw entry sagittal angle and marched bending angle of pedicle screw bar. Finally, SSA and Roussouly classification can be easily obtained with a standing lateral X-ray. Furthermore, the data changes in the supine position or during surgery. For this reason, we obtained the SSA and Roussouly classification by CT

scan in the supine position to guide screw placement.

This study has some limitations. First, though we could precisely fix the SP position and the entrance angle, this system needs convenient devices to apply the parameters during surgery. We have already planned to invent a new locating device based on this system and more studies will be conducted with this device. Another limitation is the measurement of SSA and Roussouly classification. For an obvious reason, the other five parameters will not change regardless of how the position changes. However, the SSA and Roussouly classification will change from standing to supine or prone position, especially in patients with spinal, sagittal, and coronal imbalance or lumbar instability [25,26]. In this study, we obtained measurements in the supine position by CT scan, which may be more accurate in the prone position. Therefore, we are conducting more studies regarding the change in alignment before and after surgery and surgical outcomes obtained from this system.

## Conclusion

Our localization system with six parameters, including SP-H, SP-L, TSA, SSA, W, and H, based on CT reconstruction and precise equations contributes to improved understanding of the pedicle anatomy and helps improve accuracy of lumbar spine pedicle screw placement. SSA combined with Roussouly classification could be expected to guide the establishment of sagittal alignment of the lumbar spine. Considering the accuracy, ease of use, and low-cost of the system, it is expected to be widely used in clinical practice.

## Conflict of interest

The authors declare no conflict of interest.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jot.2020.03.010.

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