Comparison of Freehand Sagittal Trajectories for Inserting Pedicle Screws Between C7 and T5

Masahito Oshina, MD, Chiaki Horii, MD,* Shima Hirai, MD,* Yoshitaka Matsubayashi, MD,* Yuki Taniguchi, MD, PhD,* Naoto Hayashi, MD, PhD,† Sakae Tanaka, MD, PhD,* and Yasushi Oshima, MD, PhD**

Study Design: Anatomic study using computed tomographic scans.

Objective: The purpose of this paper was to determine the trajectory of pedicle screw insertions, in regard to posterior bony landmarks encountered during standard posterior exposure of the spine between the seventh cervical (C7) and the fifth thoracic (T5) vertebrae, when lateral fluoroscopic and radiographic guidance may be obstructed by the scapula and shoulders.

Summary of Background Data: Only a few studies have evaluated the intraoperative sagittal trajectory of pedicle screw insertion.

Materials and Methods: We assessed 64 participants of a health screening program using whole-spine computed tomographic scans. On the basis of 5 previously reported methods, we designed 3 freehand trajectories: lamina surface method (angle between the superior vertebral endplate and the surface of the lamina), spinous process method (angle between the superior vertebral endplate and a line connecting the tips of the index spinous process and the one cephalad to it), and facet tilt method (angle between the superior endplate and the superior facet tilt). We calculated each of the angles for the C7–T5 vertebrae and determined the most reliable method using coefficients of variation (CV) and intraobserver and interobserver reliability.

Results: The lamina surface method had the smallest CVs for C7 and T1, and the mean angles were larger than 90 degrees (range, 94.7–102.4 degrees). The spinous process method had the smallest CVs between T2 and T5, and the mean angles were <90 degrees (range, 85.0–87.0 degrees). The intraobserver and interobserver reliabilities were good or excellent for both methods.

Conclusions: The ideal sagittal trajectories for pedicle screw insertion are nearly orthogonal to the lamina surface or the line connecting the spinous processes, but were different for each of the vertebrae. The lamina surface method was the most reliable for C7 and T1, whereas the spinous process method was most reliable between T2 and T5.

Level of Evidence: Level III.

Key Words: sagittal trajectory, pedicle screw, freehand, cervical, thoracic

(*Clin Spine Surg* 2018;31:E357–E362)

Recently, as surgical indications have changed, the incidence of spinal fusion surgeries has increased globally,[1] and the accuracy of pedicle screw insertion has become increasingly important for patient safety. Although the lower cervical or upper thoracic vertebrae are frequently used as the end vertebrae for fusion surgeries due to spinal deformities or ossification of the posterior longitudinal ligament, the sagittal orientation of the pedicle screw is important for avoiding adjacent segmental disease, pedicle screw loosening, and nerve root injury. However, compared with other areas of the spine,[2] inserting pedicle screws in this area is difficult and freehand pedicle screw insertion between C7 and T5 is challenging. In this spinal region, confirming whether the screws are accurately inserted in the lateral plane is often difficult when using fluoroscopy or radiography because the area is often overlapped by the scapula and/or shoulder. Therefore, in these cases, except for anterior-posterior fluoroscopic images and radiographs, we must rely on a safe freehand technique, intraoperative computed tomography (CT), or spinal navigation technology. Numerous axial trajectories and some entry points for freehand pedicle screw insertion have been discussed in the literature[3–14]; however, few studies have evaluated the intraoperative sagittal trajectory.[4,8,11–14] Although the spinal structure can only be seen from the posterior view, intraoperatively, previous sagittal trajectories are not actually "freehand"; they are unsatisfactory because they do not allow for an actual lateral view of the bony spine or lateral radiographic images.[4,11,12,14] Moreover, if intraoperative fluoroscopy or radiography is used, obtaining a clear image of the lower cervical and upper thoracic spine is difficult due to the overlapping by the shoulder and other structures.

We investigated the sagittal trajectories of pedicle screw insertion using, as anatomic references, the clear bony landmarks encountered following posterior exposure

Received for publication February 7, 2018; accepted May 8, 2018.
From the Departments of *Orthopedic Surgery; and †Computational Diagnostic Radiology and Preventive Medicine, The University of Tokyo Hospital, Tokyo, Japan.
The authors declare no conflict of interest.
Reprints: Yasushi Oshima, MD, PhD, Department of Orthopedic Surgery, The University of Tokyo Hospital, 7-3-1, Hongo, Bunkyo-Ku, Tokyo 113-8655, Japan (e-mail: yoo-tky@umin.ac.jp).

of the spine between the lower cervical and upper thoracic levels. The pedicles' sagittal trajectories, relative to these posterior bony references, were calculated using the CT scans of participants in a health screening program.

MATERIALS AND METHODS

Data Extraction

The participants included 64 volunteers (32 men and 32 women) with available whole-spine and pelvic CT scans, taken in the supine position, who participated in the University of Tokyo Hospital health screening program between 2011 and 2015. The mean participant age was 60.1 years (men, 59.9 y; women, 60.3 y) with an age range of 42–79 years (men, 42–79 y; women, 43–78 y). To avoid age bias, we evaluated 16 people from 4 age groups (40s, 50s, 60s, and 70s); sex bias was avoided by having 8 women and 8 men in each group. A preliminary investigation of 104 people showed a maximum SD of 12 for all measured parameters (described below). Therefore, a sample size of 64 people was necessary, using an estimated interval population mean that included an error (δ) of 5 degrees; the confidence level (1-α) was 95%, and the SD (σ) was 12. The data were collected and reviewed by independent researchers.

Measured Parameters

We obtained 1.25 mm slice, axial CT images (Aquilion LB; Toshiba Medical Systems, Tochigi, Japan) from the Digital Imaging and Communications in Medicine data and imported the images into a multiplanar reconstruction viewer (RadiAnt Dicom Viewer 3.4.2; Medixant, Maciej Frankiewicz, Poland). The multiplanar reconstruction viewer was used to recreate sagittal images and calculate angles.

We set morphologic characteristics from the seventh cervical vertebra (C7) to the fifth thoracic vertebra (T5). Furthermore, we calculated the C7–T5 sagittal pedicle axes of 2 freehand sagittal trajectories (I and II, described below) that were modifications of those used in previous studies[4,8,12,14]; a third trajectory (III, described below) was also evaluated using the structure of the posteriorly exposed dorsal spine. We chose C7 as the upper-end vertebra because when pedicle screw fixations are performed at our institution, those involving C7 carry a minimal risk of contacting the vertebral artery in the transverse foramen.[15,16] T5 was chosen as the lower-end vertebra because distal to the T5 sagittal pedicle, directions can be confirmed using unobstructed lateral fluoroscopy.

We searched for previous studies of freehand pedicle screw trajectories and found the full-text articles of 5 studies on sagittal freehand trajectories involving the C7–T5 pedicles[4,8,11–13] (Table 1). However, the previous sagittal trajectories were vague and difficult to apply in vivo, without lateral fluoroscopic guidance and confirmation. Therefore, assessing the sagittal angles of the lower cervical and upper thoracic vertebrae was difficult, resulting in our modification of these techniques to use the surfaces of the exposed posterior bony elements as references (I and II).

We calculated the accuracies and compared the 3 trajectories that could be used for freehand pedicle screw insertion from the dorsal spine by supposing that each trajectory involved a straightforward technique.[17] In other words, the 3 sagittal trajectories involve angles between the chosen posterior bony landmarks and the upper vertebral endplates, which indicate the pedicle direction.

(I) Lamina surface method: the angle between the superior vertebral endplate and the surface of the lateral mass (C7) or surface of the lamina (T1–T5). The reference image was set in the sagittal plane, 1 slice lateral to the center of the pedicle, with the pedicle's craniocaudal borders clearly visualized. This plane was assumed to be the inflection line from the spinous process to the transverse process, which is the starting point for inserting the pedicle screw. This method was a modification of previously published techniques in which a direction perpendicular to the long axis of the lamina,[12,14] the angle between posterior aspect of the lamina and axis of the pedicle,[13] orthogonal to the dorsal spine curvature were used[4] (Fig. 1).

(II) Spinous process method: the angle between the superior vertebral endplate and a line connecting the tip of the index spinous process and the one cephalad to it (Fig. 2). The reference image was set in the sagittal plane, bisecting the spinous process at its center. This method was a modification of a technique in which a line perpendicular to the supraspinal ligament was used.[8] For example, the C7 sagittal angle was the angle between the line connecting the tips of the C6 and C7 spinous processes and the C7 superior vertebral endplate.

(III) Facet tilt method: the angle between the superior endplate and superior facet tilt (Fig. 3). The reference image was set in the sagittal plane, 1 slice lateral to the center of the pedicle, with the pedicle's craniocaudal borders clearly visualized.

Statistical Analyses

Two spine surgeons independently calculated the interobserver reliability. The main independent observer calculated the 5 sagittal angles twice (the angles between

TABLE 1. Previous Studies on Sagittal Freehand Pedicle Screw Trajectories

References	Sagittal Trajectory	No. Patients	Spinal Level	Accuracy Rate (%)
Parker et al[11]	Parallel to the superior endplate of the segment of interest	964	T1–L5	98.3
Rivkin et al[12]	Perpendicular to the long axis of the T1 lamina	44	T1	82.8
Fennell et al[4]	Always orthogonal to the dorsal curvature of the spine at the corresponding level	33	T1–T12	96
Li et al[8]	Perpendicular to the supraspinal ligament	53	T1–L5	96.3
Stanescu et al[13]	The angle between the aspect of the lamina and pedicle axis	16	C5–T5	Not mentioned

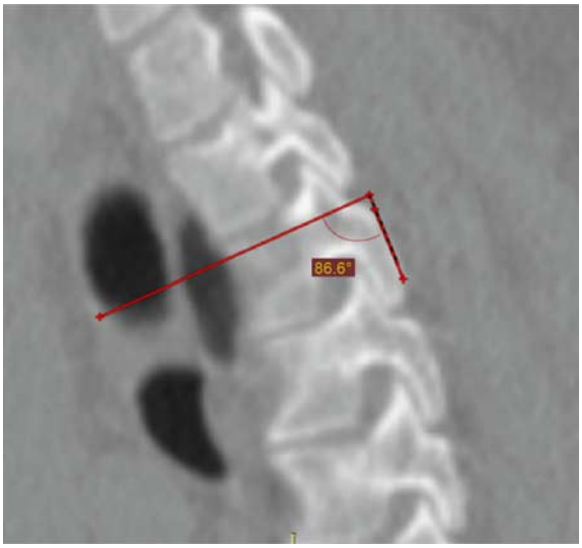

FIGURE 1. The angle between the superior vertebral endplate and the surface of the lateral mass (C7) or the surface of the lamina (T1–T5).

FIGURE 3. The angle between the superior vertebral endplate and superior facet tilt.

the upper endplate and left and right facet tilts, the angle between the upper endplate and the line connecting the spinous process tips, and the angle between the upper endplate and left and right laminal surfaces). Both independent observers measured 5 sagittal angles for each subject. The intraobserver reliability was calculated using the reliability statistics of the intraclass correlation (ICC 1, 2) for the angles. The interobserver reliability was calculated using the reliability statistics of the interclass correlation (ICC 2, 1) for the angles. The cutoff was determined for both ICC types, according to the research protocol. The intraclass and interclass correlation values were graded as: 0.8–1.0, excellent; 0.6–0.8, good; 0.4–0.6, moderate; and 0.0–0.4, poor.

To assess data scattering, we evaluated which of the 3 trajectories was the most reliable using coefficients of variation (CVs). CVs were used to compare each method's angles among the participants. A low CV indicated low data scattering that was unaffected by individual differences, making it useful for evaluating the study participants. Paired *t* tests were used to analyze the angles between the different sides; a *P*-value <0.05 was considered statistically significant. The statistical software, R, version 2.8.1 (The R Foundation for Statistical Computing, Vienna, Austria) was used for the statistical analyses.

RESULTS

Of the 3 methods used, the lamina method was associated with the smallest CVs for C7 and T1, whereas the spinous process method had the smallest CVs for vertebrae between T2 and T5. The CVs of the facet tilt method were inferior to those of the other methods (Table 2). No significant difference was observed between the different sides of the sagittal angle parameters.

The angle for the lamina surface method was almost orthogonal, but slightly larger in C7 (right, 102.3 ± 6.1 degrees; left, 102.4 ± 6.6 degrees) and T1 (right, 95.8 ± 4.8 degrees; left, 94.7 ± 5.4 degrees). The angle was almost orthogonal for the spinous process method as well, but became smaller from T2–T5 (T2, 87.0 ± 3.1 degrees; T3, 86.5 ± 2.9 degrees; T4, 85.2 ± 2.8 degrees; T5, 85 ± 2.8 degrees). For the facet tilt method, the angle ranged from 61.5 degrees (T1) to 71.3 degrees (T5) (Table 2).

The intraobserver reliability was good or excellent for all sagittal angles in the lamina surface (ICC, 0.69–0.85), spinous process (ICC, 0.71–0.97), and facet tilt (ICC, 0.71–0.85) methods. The interobserver reliability was also good or excellent for all sagittal angles in the

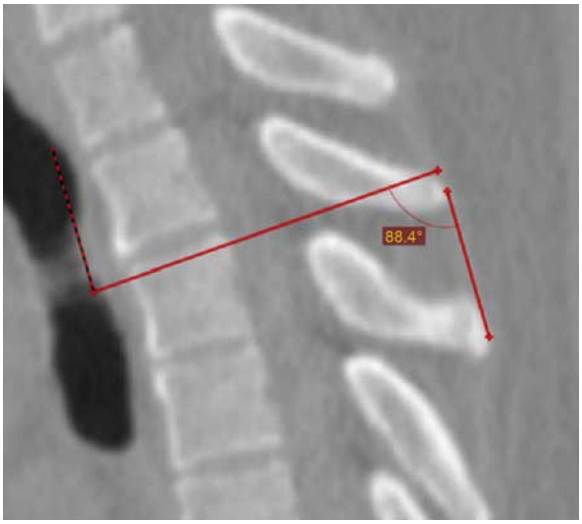

FIGURE 2. The angle between the superior vertebral endplate and a line connecting the tips of the index spinous process and the one cephalad to it.

TABLE 2. Differences (Mean ± SD, CV, and Range of Angle) Among the Facet Tilt, Lamina Surface, and Spinous Process Methods for Angle Calculations

Trajectory	C7 R Lamina	C7 L Lamina	T1 R Lamina	T1 L Lamina	T2 R Lamina	T2 L Lamina	T3 R Lamina	T3 L Lamina	T4 R Lamina	T4 L Lamina	T5 R Lamina	T5 L Lamina
Mean ± SD (deg.)	102.3 ± 6.1	102.4 ± 6.6	95.8 ± 4.8	94.7 ± 5.4	90.9 ± 5.2	89.9 ± 5.7	90.7 ± 5.5	89.6 ± 5.9	91.3 ± 5.4	89.5 ± 6.2	91.0 ± 4.1	90.3 ± 4.9
CV	0.059	0.064	0.050	0.057	0.058	0.063	0.060	0.066	0.059	0.070	0.045	0.055
Angle (range) (deg.)	87.0–116.1 (29.1)	89.7–118.8 (29.1)	82.9–106.1 (23.2)	77.9–107.7 (29.8)	80.2–106.1 (25.9)	75.7–106.3 (30.6)	79.4–103.6 (24.2)	73.3–103.3 (30.0)	78.5–107.7 (29.2)	74.6–105.7 (31.1)	82.3–100.2 (17.9)	80.7–102.2 (21.5)
	C7 Spinous		T1 Spinous		T2 Spinous		T3 Spinous		T4 Spinous		T5 Spinous	
Mean ± SD (deg.)	112.5 ± 12.7		93.8 ± 5.3		87.0 ± 3.1		86.5 ± 2.9		85.2 ± 2.8		85.0 ± 2.8	
CV	0.11		0.056		0.036		0.033		0.032		0.033	
Angle (range) (deg.)	92.5–144.9 (52.4)		83.2–106.3 (23.1)		80.4–93.0 (12.6)		80.6–94.6 (14.0)		80.2–90.5 (10.3)		80.2–94.6 (14.4)	
	C7 R Facet	C7 L Facet	T1 R Facet	T1 L Facet	T2 R Facet	T2 L Facet	T3 R Facet	T3 L Facet	T4 R Facet	T4 L Facet	T5 R Facet	T5 L Facet
Mean ± SD (deg.)	64 ± 7.3	62.7 ± 6.9	61.5 ± 7.7	60.5 ± 7.9	65.4 ± 6.4	65.3 ± 6.0	68.5 ± 5.0	68 ± 4.5	69.7 ± 4.6	71 ± 5.0	70.1 ± 5.1	71.3 ± 5.0
CV	0.11	0.11	0.13	0.13	0.098	0.093	0.073	0.066	0.066	0.071	0.073	0.071
Angle (range) (deg.)	46.4–77.0 (30.6)	38.8–75.5 (36.7)	42.6–75.8 (33.2)	41.2–77.3 (36.1)	47.6–76.0 (28.1)	53.0–79.9 (26.9)	52.5–77.2 (24.7)	54.4–78.6 (24.2)	52.9–80.7 (27.8)	60.4–82.8 (22.4)	54.5–81.3 (26.8)	57.8–82.9 (25.1)

The shaded areas indicate the smallest CV value among the 3 methods. A low CV indicates low data scattering between participants. Range indicates the range of angles determined for each participant.
CV indicates coefficient of variation; facet, facet tilt method; L, left; lamina, lamina surface method; R, right; spinous, spinous process method.

lamina surface (ICC, 0.66–0.86), spinous process (ICC, 0.66–0.91), and facet tilt (ICC, 0.61–0.70) methods (Table 3).

DISCUSSION

We sought to determine the ideal sagittal trajectory for pedicle screw insertion, based on the clear anatomic landmarks identified during standard posterior exposure of the spine, between C7 and T5. We found that the lamina method was the most reliable for C7 and T1, whereas the spinous process method was the most reliable method for the T2–T5 vertebrae.

Numerous studies have reported on freehand pedicle screw insertion but have only evaluated the starting point and axial trajectories. We found only 5 studies that evaluated freehand sagittal trajectories, and none of the trajectories were usable, in situ, without the assistance of fluoroscopy, radiography, or special devices. Moreover, these studies only evaluated areas orthogonal to the spine curvature or perpendicular to the long axis of the laminae.[4,12] These trajectories are vague or hard to use intraoperatively, and the existence of a 90 degrees angle between all spinal vertebrae is unlikely.

Fennell et al[4] reported that the freehand sagittal trajectory was orthogonal to the dorsal spine curvature at the corresponding level. However, consecutive spinal vertebrae and the dorsal spinal curvature cannot be seen when only exposing the spine posteriorly because the skin and muscle interrupt the view of the whole spinal construct. Hence, a vague definition of the dorsal curvature may mislead the surgeon when securing the orthogonal direction. In fact, various authors initially used radiographs, but in the lower cervical and upper thoracic spine, the dorsal spine curvature cannot be seen clearly because the view is interrupted by the scapula and shoulder. Similarly, Rivkin et al[12] and Yan et al[14] reported that the sagittal trajectory is perpendicular to the long axis of the lamina. However, the long axis of the lamina is unclear in a dorsal view of the spine because the cranial edge of the long axis cannot be visualized underneath the inferior facet and the lamina shape is complicated. Stanescu et al[13] measured the angle between the posterior aspect of the lamina and the pedicle axis by placing 1 arm of a goniometer on the posterior aspect of the lamina. Although a detailed explanation of the measurement method was not presented, considering the morphology, the posterior aspect of the lamina indicated not only the lamina surface, but also the superior facet surfaces. Thus, in order to clearly understand the results, we modified these 2 methods as the surface of the lamina or lateral mass. In this method, the sagittal angles were slightly greater than orthogonal, measuring ~100 degrees (C7) and 95 degrees (T1).

Regarding the spinous process method, Li et al[8] reported that a pedicle screw should be inserted perpendicular to the supraspinal ligament. We modified this method because the supraspinal ligaments are sometimes unclear and are not regularly curved; therefore, we used the line

TABLE 3. Intraobserver and Interobserver Reliability Analysis

Method	Intra	Inter	Method	Intra	Inter	Method	Intra	Inter
C7 R lamina	0.77	0.70	C7 spinous	0.97	0.91	C7 R facet	0.79	0.62
C7 L lamina	0.79	0.81				C7 L facet	0.85	0.62
T1 R lamina	0.75	0.75	T1 spinous	0.89	0.77	T1 R facet	0.82	0.70
T1 L lamina	0.79	0.84				T1 L facet	0.81	0.65
T2 R lamina	0.69	0.67	T2 spinous	0.82	0.66	T2 R facet	0.79	0.65
T2 L lamina	0.81	0.76				T2 L facet	0.74	0.61
T3 R lamina	0.73	0.76	T3 spinous	0.72	0.68	T3 R facet	0.71	0.63
T3 L lamina	0.69	0.86				T3 L facet	0.72	0.64
T4 R lamina	0.80	0.77	T4 spinous	0.77	0.71	T4 R facet	0.73	0.63
T4 L lamina	0.73	0.87				T4 L facet	0.77	0.70
T5 R lamina	0.85	0.66	T5 spinous	0.71	0.76	T5 R facet	0.79	0.61
T5 L lamina	0.78	0.81				T5 L facet	0.80	0.62

The intraclass and interclass correlation values were graded as: 0.8–1.0, excellent; 0.6–0.8, good; 0.4–0.6, moderate; and 0.0–0.4, poor.
facet indicates facet tilt method; L, left; lamina, lamina surface method; R, right; spinous, spinous process method.

connecting the tips of the spinous processes. As a result, the sagittal angles were about 85 degrees between T2 and T5. We also used CT data for determining angles, whereas previous studies used magnetic resonance imaging. This methodological difference may explain the differences between our results and those previously published. We believe that CT-derived angles are more reliable than those determined using magnetic resonance imaging.

The spinous process method was associated with the smallest CVs between T2 and T5 in this study. Since the spinous process method uses 2 consecutive spinous processes, the participant's posture may affect the method. CT was performed with each participant in the supine position, but surgeries are performed with the patient in the prone position, possibly resulting in differences in the positional relationships between the spinous processes. Although the angles may vary between the supine and prone positions, Brink et al[18] reported only a 5 degrees of difference in the overall thoracic kyphosis between the 2 positions, even in adolescent individuals with idiopathic scoliosis. Therefore, the supine-prone positions are inconsequential to the measurements because the intervertebral angle averages <0.5 degrees. Moreover, compared with the cervicothoracic junction (C7–T1) located closer to the middle thoracic vertebrae, the difference between the prone and supine positions was less affected by posture or head position because the spinal flexibility was reduced by the stability of the rib cage. Therefore, between T2 and T5, the spinous process method is the most reliable because there is an 87.0–85.0 degrees angle between the superior vertebral endplate and a line connecting the tips of the index spinous process and the one cephalad to it. The sagittal trajectory should be set orthogonal to the line connecting the spinous processes and then directed about 5 degrees caudally. If large postural differences clearly exist between the supine and prone positions, the lamina surface method is recommended. If the lamina surface method is used, the angle is ~90 degrees (orthogonal) between the structures.

For the facet tilt method, the angles were relatively scattered. This is because the facet shape changes as degeneration occurs and the facet tilt also changes; therefore, the extent of the angle changes reflect individual differences.

Finally, when fluoroscopic guidance is not feasible or unavailable, safe pedicle screw insertions may still be performed between C7 and T1. Although acquiring additional information using 3-dimensional fluoroscopy or a navigation system may increase safety, utilizing the posterior spinal anatomy as a reference for freehand pedicle screw instrumentation has the potential for reducing radiation exposure and improving surgical time. Moreover, increased surgeon technical expertise will also reduce the risk of pedicle screw misplacement.

There are several limitations to the current study. First, we only used a straightforward method to determine the angles; namely, we used the direction parallel to the upper endplate, and we did not evaluate the anatomic trajectory or other methods.[17] Other studies should investigate these other trajectories. Second, for patients with severely degenerated or deformed spines, changes in the deformed and degenerated shape of the spinal structures may lead to different results. In particular, our methods may not apply to patients with osteoporosis due to their having deformations of the superior endplates and increased risks of endplate violations. Therefore, all patients should undergo their own anatomic evaluation to determine the entry point and screw direction. Third, because our trajectories were not clinically tested and we did not actually insert pedicle screws, the accuracy of pedicle screw insertion using our sagittal trajectory method is uncertain.

In summary, the ideal sagittal trajectories for pedicle screw insertions are nearly orthogonal to the lamina surface or to the line connecting spinous processes but were different for each of the vertebrae. The lamina surface method was the most reliable for the C7–T1 vertebrae, and the sagittal angles were slightly larger than orthogonal. However, the spinous process method was the most reliable for vertebrae between T2 and T5, and the sagittal angles were slightly smaller than orthogonal. The knowledge gained from our study will provide surgeons with a better understanding of the direction in which pedicle screws should be inserted.

REFERENCES

1. Oglesby M, Fineberg SJ, Patel AA, et al. Epidemiological trends in cervical spine surgery for degenerative diseases between 2002 and 2009. *Spine (Phila Pa 1976)*. 2013;38:1226–1232.
2. Kwan MK, Chiu CK, Gani SM, et al. Accuracy and safety of pedicle screw placement in adolescent idiopathic scoliosis patients: a review of 2020 screws using computed tomography assessment. *Spine (Phila Pa 1976)*. 2017;42:326–335.
3. Avila MJ, Baaj AA. Freehand thoracic pedicle screw placement: review of existing strategies and a step-by-step guide using uniform landmarks for all levels. *Cureus*. 2016;8:e501.
4. Fennell VS, Palejwala S, Skoch J, et al. Freehand thoracic pedicle screw technique using a uniform entry point and sagittal trajectory for all levels: preliminary clinical experience. *J Neurosurg Spine*. 2014;21:778–784.
5. Karapinar L, Erel N, Ozturk H, et al. Pedicle screw placement with a free hand technique in thoracolumbar spine: is it safe? *J Spinal Disord Tech*. 2008;21:63–67.
6. Kim YJ, Lenke LG, Bridwell KH, et al. Free hand pedicle screw placement in the thoracic spine: is it safe? *Spine (Phila Pa 1976)*. 2004;29:333–342.
7. Lehman RA Jr, Kang DG, Lenke LG, et al. The ventral lamina and superior facet rule: a morphometric analysis for an ideal thoracic pedicle screw starting point. *Spine J*. 2014;14:37–144.
8. Li J, Zhao H, Xie H, et al. A new free-hand pedicle screw placement technique with reference to the supraspinal ligament. *J Biomed Res*. 2014;28:64–70.
9. Modi H, Suh SW, Song HR, et al. Accuracy of thoracic pedicle screw placement in scoliosis using the ideal pedicle entry point during the freehand technique. *Int Orthop*. 2009;33:469–475.
10. Modi HN, Suh SW, Hong JY, et al. Accuracy of thoracic pedicle screw using ideal pedicle entry point in severe scoliosis. *Clin Orthop Relat Res*. 2010;468:1830–1837.
11. Parker SL, McGirt MJ, Farber SH, et al. Accuracy of free-hand pedicle screws in the thoracic and lumbar spine: analysis of 6816 consecutive screws. *Neurosurgery*. 2011;68:170–178.
12. Rivkin MA, Okun JF, Yocom SS. Novel free-hand T1 pedicle screw method: review of 44 consecutive cases. *J Neurosci Rural Pract*. 2014;5:349–354.
13. Stanescu S, Ebraheim NA, Yeasting R, et al. Morphometric evaluation of the cervico-thoracic junction. Practical considerations for posterior fixation of the spine. *Spine (Phila Pa 1976)*. 1994;19: 2082–2088.
14. Yan J, Li K, Zheng Y, et al. The ipsilateral adjacent laminae: a reliable guide in determining the direction of subaxial cervical pedicle axis in the sagittal plane. *Spine (Phila Pa 1976)*. 2015;40:1647–1652.
15. Keskin F, Erdi F, Nayman A, et al. Radiological anatomy of the C7 vertebra: clinical implications in spine surgery. *J Craniovertebr Junction Spine*. 2015;6:30–35.
16. Wakao N, Takeuchi M, Kamiya M, et al. Variance of cervical vertebral artery measured by CT angiography and its influence on C7 pedicle anatomy. *Spine (Phila Pa 1976)*. 2014;39:228–232.
17. Lehman RA Jr, Polly DW Jr, Kuklo TR, et al. Straight-forward versus anatomic trajectory technique of thoracic pedicle screw fixation: a biomechanical analysis. *Spine (Phila Pa 1976)*. 2003;28: 2058–2065.
18. Brink RC, Colo D, Schlösser TP, et al. Upright, prone, and supine spinal morphology and alignment in adolescent idiopathic scoliosis. *Scoliosis Spinal Disord*. 2017;12:6.