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ORIGINAL

COMPARATIVE ASSESSMENT OF THORACIC AND LUMBAR PEDICLE SCREW FIXATION ACCURACY IN EARLY-ONSET CONGENITAL SCOLIOSIS AND ITS IMPLICATIONS FOR POSTOPERATIVE FUNCTIONAL RECOVERY

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ABSTRACT

Objective: This study evaluates the accuracy of freehand thoracolumbar pedicle screw placement in children with early-onset congenital scoliosis using CT imaging, aiming to optimize surgical strategies and enhance postoperative functional recovery in young patients. **Methods:** A total of 26 hospitalized children with early-onset congenital scoliosis (16 males, 10 females; aged 2–10 years, mean age 4.68 ± 2.42 years) who underwent pedicle screw fixation from December 2014 to December 2019 were retrospectively analyzed. Freehand pedicle screw insertion was performed using C-arm guidance combined with anatomical markers, covering T1–L5 vertebral levels. The accuracy of screw placement was graded based on penetration distance through the medial, lateral, or anterior bone cortex: Grade 1 (<2mm, accurate placement), Grade 2 (2–4mm, minor deviation), and Grade 3 (>4mm, significant deviation). Grades 2 and 3 were classified as abnormal placements. Postoperative complications related to screw insertion were also recorded. **Results:** A total of 173 pedicle screws were inserted (mean: 6.73 screws per patient). Accurate placement (Grade 1) was achieved in 143 screws (82.7%), while 30 screws (17.3%) showed abnormal placement, including 24 Grade 2 (13.9%) and 6 Grade 3 (3.5%). Abnormal placements were more common in thoracic vertebrae (Grade 2: 20; Grade 3: 5) than in lumbar vertebrae (Grade 2: 4; Grade 3: 1), with a statistically significant difference ($\chi^2 = 5.801$, $P < 0.05$). Additionally, screw misplacement was significantly higher on the concave side (55.6%, 15/27) compared to the convex side (20.1%, 7/34); $\chi^2 = 23.047$, $P < 0.05$. No intraoperative or postoperative complications related to screw insertion were observed. **Conclusion:** Freehand placement of thoracic and lumbar pedicle screws in children under 10 years of age with early-onset congenital scoliosis demonstrates high accuracy and minimal complications, supporting its safety and clinical feasibility. However, greater caution is required when placing screws in thoracic vertebrae and morphologically abnormal vertebrae, particularly on the concave side, to minimize risks and optimize spinal stability. Future research should explore the impact of pedicle screw accuracy on postoperative rehabilitation and functional mobility outcomes in pediatric scoliosis patients.

KEYWORDS: Thoracic and Lumbar Vertebra; Early-Onset Congenital Scoliosis; Pedicle Screw; Accuracy

1. INTRODUCTION

Early-onset congenital scoliosis (ECS) is a complex spinal deformity that arises due to vertebral malformations during fetal development, leading to progressive curvature of the spine in young children. The condition not only affects spinal alignment but also has significant implications for pulmonary function, physical activity, and overall quality of life. Surgical correction is often required to prevent severe deformity progression and associated complications. Among the various surgical techniques, thoracic and lumbar pedicle screw fixation has gained prominence due to its ability to provide rigid segmental stabilization, improved deformity correction, and enhanced postoperative functional recovery. However, achieving accurate pedicle screw placement in pediatric patients presents unique challenges due to the small size of vertebrae, anatomical variations, and the presence of morphologically abnormal vertebrae. Unlike adults, the pedicles in children are significantly narrower, and their cortical thickness is thinner, increasing the risk of screw misplacement, neurological injury, and vascular complications. The challenge is further amplified in ECS cases, where vertebral anomalies such as hemivertebrae, fused vertebrae, and wedge-shaped deformities distort normal anatomical landmarks. While image-guided navigation and robotic-assisted placement have been proposed to enhance precision, these techniques are not always feasible in pediatric spinal surgeries due to increased operative time, radiation exposure, and resource constraints. Consequently, many surgeons rely on freehand pedicle screw placement, guided by intraoperative fluoroscopy and anatomical landmarks. However, the accuracy and safety of this approach in ECS patients remain under investigation. The accuracy of pedicle screw insertion is critical to achieving biomechanical stability, reducing the risk of spinal cord injury, and ensuring optimal functional recovery. Inaccurate placement, particularly medial or lateral breaches, can lead to neurological deficits, vascular injury, and implant failure, which may compromise the patient's ability to engage in post-surgical rehabilitation and physical activities. Additionally, given that pediatric patients have higher bone remodeling capacity and longer life expectancy, long-term stability of the fixation is essential to support growth-friendly surgical strategies and prevent reoperations. This study aims to evaluate the accuracy of freehand pedicle screw placement in thoracic and lumbar vertebrae of children with ECS using postoperative computed tomography (CT) assessment. By analyzing the placement accuracy across different spinal regions and morphologically abnormal vertebrae, we seek to provide clinical insights into optimizing surgical techniques and improving patient outcomes. Furthermore, we examine complication rates associated with screw insertion to determine the safety profile of this technique in young children (Qiu et al., 2023). Given the journal's focus on physical activity and sports medicine, this study also highlights the implications of pedicle screw placement accuracy on postoperative rehabilitation, spinal mobility, and functional recovery. Proper screw placement contributes to spinal stability and alignment, which are essential for restoring mobility, promoting early ambulation, and enabling pediatric patients to participate in physical activities. Understanding the factors influencing screw misplacement can help refine surgical techniques, reduce complications, and enhance the overall recovery process, allowing young patients to regain better postural control, muscle strength, and movement efficiency (Baghdadi et al., 2013). This study aims to compare the accuracy of thoracolumbar pedicle screw placement in children with early-onset congenital scoliosis using CT analysis and to provide a clinical reference for free-hand pedicle screw placement.

2. Material and Methods

2.1 General Information

A total of 26 patients were included in this study, including 16 males and 10 females, aged from 2 to 10 years, with an average age of (4.68±2.42) years. The preoperative Cobb Angle was 16.3-57.6 degrees, with an average of 32.74±8.62 degrees. The postoperative Cobb Angle was 1.2-21.2 degrees, with an average of 7.15±5.09 degrees.

2.2 Inclusion and Exclusion Criteria

Inclusion criteria: (1) age ≤10 years old; (2) congenital scoliosis of the thoracic and/or lumbar spine; (3) preoperative and postoperative CT examinations were performed in all patients.

Exclusion criteria: (1) previous history of spinal surgery; (2) anterior spinal surgery was performed. (3) idiopathic scoliosis, neuromuscular scoliosis, and syndromic scoliosis.

2.3 Procedure of Surgery

2.3.1 Preoperative Evaluation

Firstly, the fusion range was determined according to the preoperative anteroposterior and lateral view of the whole spine and spinal CT. The transverse diameter of the pedicle was determined by measuring the inner diameter of the isthmus of the pedicle on the image section of the widest slice of the transverse section of the pedicle parallel to the longitudinal axis of the pedicle. A straight line was drawn to the anterior edge of the vertebral body through the midpoint of this transverse diameter and bisected the pedicle. This line was taken as the basis for selecting the length of the pedicle screw. The diameter and length of pedicle screws were determined according to the results of the preoperative CT evaluation. The length of the screw ranged from 25 to 45cm, and the diameter ranged from 3.5mm to 5.5mm.

2.3.2 Pedicle Screw Placement

Subperiosteal dissection was performed to expose the spinous process, lamina, facet joint, and transverse process through a posterior median spinal approach. The entry point of the thoracic spine was selected at the intersection of the vertical line at the midpoint of the facet joint and the horizontal line at the upper third of the transverse process. For the lumbar spine, the intersection of the vertical line of the lateral border of the facet joint and the horizontal line of the midpoint of the transverse process was selected as the entry point. The cortical bone at the nail entry point was removed with a rongeur to expose the cancellous bone. After 1.5mm Kirschner wire positioning, C-arm fluoroscopy was used to determine the entry point. A 1.5cm marker needle was used to mark the lesion. After the direction of needle insertion was confirmed by C-arm fluoroscopy, the rigid probe was used to establish the screw path along the cancellous bone path of the pedicle. The soft probe was used to check the entry point and passage of the pedicle again, and then the pedicle screw was placed by free hand. Finally, an X-ray fluoroscopy was performed to confirm that the screw insertion was satisfactory. For patients with bone bridge and costal deformity, the location of the deformity should be determined before pedicle screw placement, and then the bone bridge and costal resection should be performed. Somatosensory evoked potential (SEP) + motor evoked potential (MEP) monitoring throughout the operation. For patients with hemivertebra deformity, complete resection of the hemivertebra was performed after pedicle screw placement.

2.4 Indicators of Evaluation

Measurements were made twice on thin-section CT by the same orthopedic surgeon using ImageJ software and averaged. The measurement index was the distance from the location of the pedicle screw breaking through the vertebral body (including the pedicle) to the inner wall, outer wall, or the anterior edge of the vertebral body (Figure 1), which was divided into three grades. Grade 1: < 2mm; Grade 2 2:2-4mm; Grade 3 3: > 4 mm (Baghdadi et al., 2013) (Figure 1).

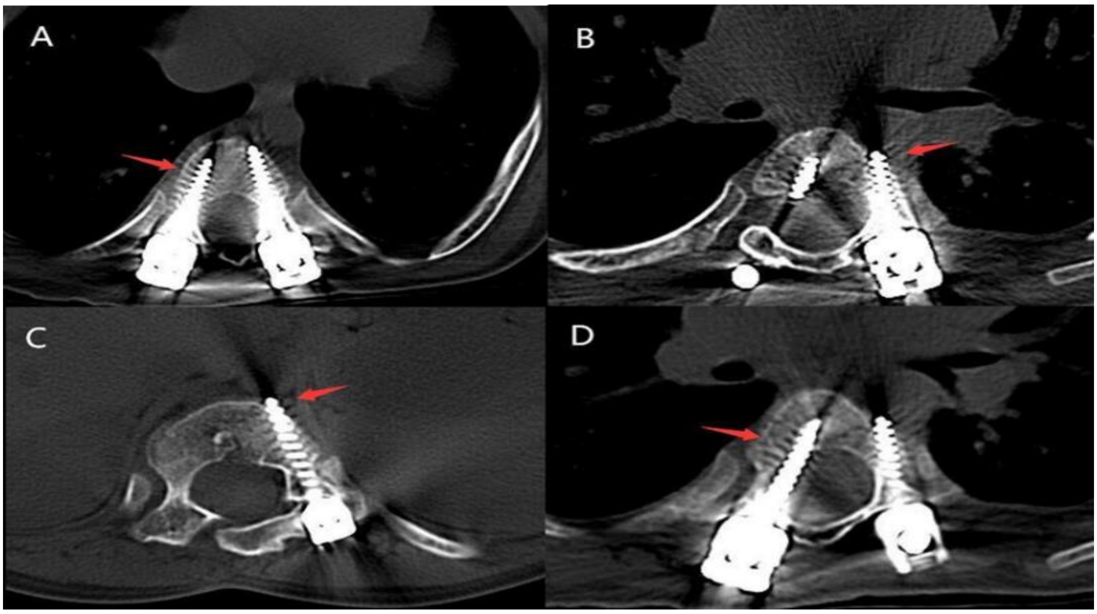

Figure 1: The accuracy grading of pedicle screw placement as shown by plain CT scan is shown. A and B show the Grade 1 placement of the screws, which penetrated the vertebral cortex less than 2mm away. C shows the Grade 2 placement of the screws, which penetrate the cortex of the vertebral body 2-4mm away. D shows the Grade 3 placement of the screw, which penetrates the vertebral cortex more than 4mm away. The corresponding level is indicated by the arrow.

Among them, Grade 1 screw placement was defined as accurate screw placement and non-first-order screw placement was defined as abnormal screw placement. At the same time, whether complications related to pedicle screw placement were found intraoperatively or postoperatively was recorded. According to the location of the screws (thoracic or lumbar segment, convex or concave side, normal or abnormal morphology of the vertebrae), the difference in the abnormal screw placement rate was analyzed. The vertebral bodies with abnormal morphology had congenital abnormalities such as butterfly vertebrae, block vertebrae, and bone bridge junction. The vertebral body with normal morphology was the vertebral body without abnormal morphology. Safety evaluation refers to the occurrence of adverse outcomes caused by pedicle screw placement during or after surgery, including hemopneumothorax, pedicle fracture, nerve root injury, aortic injury, screw loosening, extraction and breakage, spinal cord injury, etc.

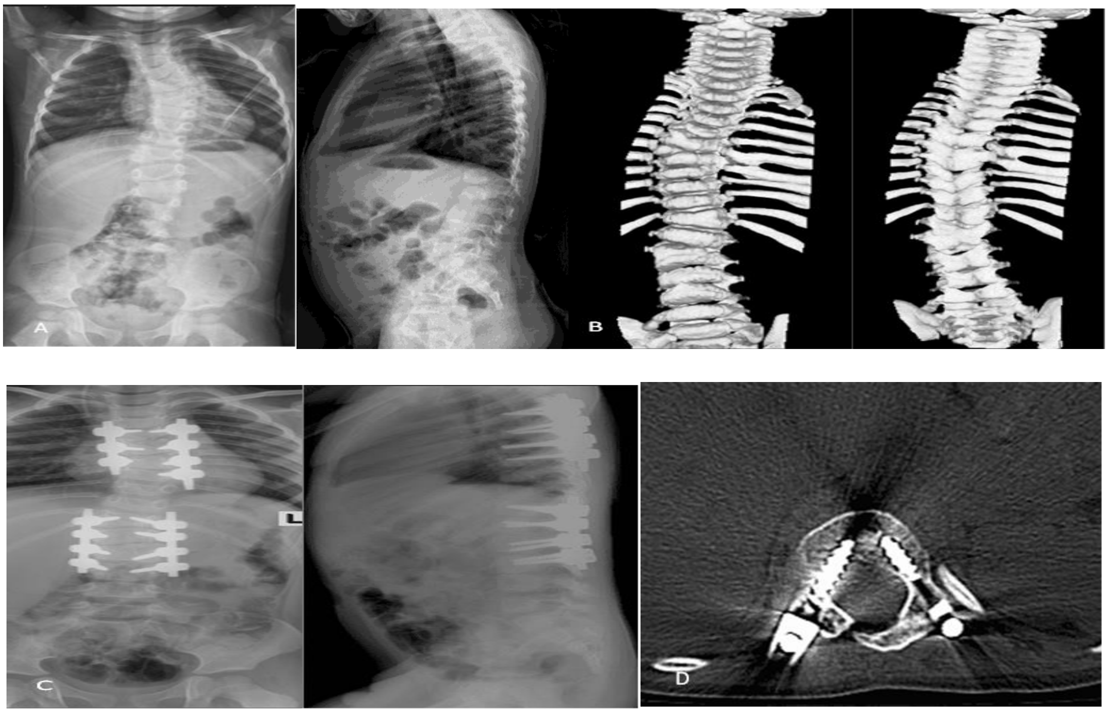

Figure 2: The above picture shows a 2-year-old boy with hemivertebra deformity at left T5, T7, right T12, and left L2, who underwent hemivertebra resection and pedicle screw fixation for scoliosis correction. A show the preoperative anteroposterior and lateral X-ray of the whole spine; the preoperative thoracic curve was 26.1 degrees and the lumbar curve was 25.6 degrees. B shows the 3D image of the spine CT. C is the postoperative anteroposterior and lateral X-ray of the whole spine. The postoperative thoracic curve was 4.2 degrees and the lumbar curve was 3.3 degrees. D shows the right thoracic 4 pedicle screw, which broke through the medial wall of the pedicle by 4mm and was a Grade 2 screw placement.

2.5 Statistical Analysis

SPSS 25.0 software was used to analyze the data. Measurement data conforming to normal distribution were represented as mean ± SD, and count data were represented as cases and percentages. The χ^2 test was used for comparison between groups. A $P<0.05$ was considered statistically significant.

3. Results

A total of 26 patients hospitalized from December 2014 to December 2019 were included in this study, and the minimum follow-up time was 1 year. A total of 173 pedicle screws were inserted, with an average of 6.7 screws (4 to 11) per patient. One hundred and forty-three screws (82.7%) were placed accurately. There were 30 abnormal screws, including 24 screws in the Grade 2 (13.9%), 6 screws in the Grade 3 (3.5%), 25 screws in the thoracic spine (14.5%) and 5 screws in the lumbar spine (2.9%). There were 8 abnormal screws in the normal vertebral body (4.6% of the total number of vertebral bodies, 71.4% of the total number of normal vertebral bodies) and 22 abnormal vertebral bodies (12.7 of the total number of vertebral bodies, 36.7% of the total number of abnormal vertebral bodies). A total of 79 screws were placed on the concave side, of which 17 were abnormal (9.8%). A total of 81 screws were placed on the convex side, and 13 screws were abnormal (75.1%). The specific data results are shown in Tables 1-5. No complications related to pedicle screw placement occurred during and after the operation. There was no obvious abnormality in the movement of the lower limbs. There were no neurological complications or other complications related to pedicle screw placement during the operation and follow-up. However, poor wound healing occurred in one patient, and the wound healed well after cleaning and dressing change.

Table 1: Comparison of Screw Placement Accuracy Between Thoracic Vertebra and Lumbar Vertebra

GROUP	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT
THORACIC VERTEBRA	111	86	25
LUMBAR VERTEBRA	62	57	5

Note: *χ^2=5.081 P<0.05.*

Table 2: Comparison of Screw Placement Accuracy Between Thoracic Vertebra and Lumbar Vertebra

GROUP	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT
CONCAVE	79	62	17
CONVEX	94	81	13

Note: *χ^2=1.771 P<0.05.*

Table 3: Comparison of Screw Placement Accuracy Between Normal and Abnormal Morphology Vertebra

GROUP	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT
NORMAL VERTEBRA	112	104	8
ABNORMAL MORPHOLOGY VERTEBRA	61	39	22

Note: *χ^2=23.047 P<0.05.*

Table 4: Comparison of Screw Placement Accuracy Between Normal Vertebra and Abnormal Morphology Vertebra with Thoracic/Lumbar Vertebra

GROUP	NORMAL VERTEBRA			ABNORMAL MORPHOLOGY VERTEBRA		
	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT
THORACIC VERTEBRA	70	64	6	41	22	19
LUMBAR VERTEBRA	42	40	2	20	17	3

Table 5: Comparison of Screw Placement Accuracy Between Normal Vertebra and Abnormal Morphology Vertebra with Concave/Convex Side

GROUP	NORMAL VERTEBRA			ABNORMAL MORPHOLOGY VERTEBRA		
	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT	N	ACCURATE PLACEMENT	ABNORMAL PLACEMENT
CONCAVE	52	50	2	27	12	15
CONVEX	60	54	6	34	27	7

Note: *Normal vertebra,* χ^2*=0.798 P>0.05; abnormal vertebra,* χ^2*=7.980 P<0.05.*

4. Discussion

With the continuous development of spinal surgery technology, the application of pedicle screws in the treatment of spinal deformity has become more and more mature and common. Especially in children with scoliosis, more and more applications, and the application age is getting younger and younger, so it can get more effective treatment intervention. Congenital scoliosis is caused by asymmetric growth of the spine caused by abnormal vertebral development at 4-6 weeks of gestation, which is due to vertebral segmental disorder, formation disorder, or both. The severity of the associated spinal deformity varies according to the type and location of the deformed vertebral body. With the growth of the patient's age, if the degree of deformity gets worse, it will further affect the patient's other system functions, such as cardiopulmonary function dysplasia, spinal cord compression, etc. In this case, non-surgical treatment generally difficult to obtain a good therapeutic effect. Cast or brace treatment also provides the clinician with an option, often only delaying the age of the patient at the time of surgical intervention. Pedicle screw fixation can provide the stability of the anterior, middle, and posterior columns of the spine, based on which the three-dimensional deformity of the spine can be corrected. The young age, immature skeletal development, and the presence of vertebral deformity make it more difficult to implant pedicle screws in patients with early-onset congenital scoliosis. Some studies (Seo et al., 2013) have suggested that thoracic and/or lumbar pedicle screw fixation is safe and effective in various types of spinal diseases under the age of 10 years. However, abnormal screw placement still cannot be ignored. The occurrence of abnormal screw placement depends on the severity of the deformity and the screw placement technique of the surgeon, but the actual incidence may be higher because most patients with abnormal screw placement are often not easy to be found because they have no clinical symptoms (Sarwahi, Suggs, et al., 2014). In adults, the tolerance of pedicle screws is relatively large, and complications are rare. However, once complications occur in adults or children, the consequences are often serious (Hicks et al., 2010). At the same time, the growth potential of children is greater than that of adults. Although many studies (Brown et al., 1998; Harimaya et al., 2011; Ruf & Harms, 2002; Sakai et al., 2008) have shown that pedicle screw fixation in children rarely causes related complications and clinical symptoms, we still want to achieve the maximum accuracy of screw placement. Asymptomatic screws can act as a "ticking time bomb" for children that will explode at some point. Growth and deformity progression may lead to implant "displacement", and the growth of the spine relative to the implant may cause the implant to protrute into the spinal canal or cause damage to peripheral nerves. It has been reported in the literature that two cases of spinal pedicle screw fixation were followed up for 2 years and 6 years respectively, and the patients developed clinical symptoms, and the pedicle screw was observed to be displaced and reshaped during the following operation (Fernandes et al., 2019). The study by Canavese et al. (Canavese et al., 2017) reported a patient with neurological symptoms caused by displacement of the fixation rod to the spinal canal 5 years after surgery. Because of the tremendous growth potential of children, it is of great benefit to analyze the accuracy of pedicle screw placement in pediatric spinal patients for safety reasons. To provide a reference for clinical practice, we studied the accuracy of pedicle screw placement in the thoracic and lumbar spine of early-onset (< 10 years old) congenital scoliosis by hand. Studies have shown that when the vertebral body is deformed, the incidence of poor screw placement is higher when free-hand screw placement is used than that of the normal vertebral body (Heidenreich et al., 2015). We reached the same conclusion: our accuracy of screw placement was 104/112 for normal vertebral bodies and 39/61 for abnormal vertebral bodies. At the same time, our study found that the concave side of the vertebral body with abnormal morphology was more likely to have malinsertion. Studies have shown that the severity of pedicle deformity is particularly obvious on the concave side of idiopathic scoliosis (Sarwahi, Sugarman, et al., 2014), that is, the pedicle on the concave side is more poorly developed and smaller than that on the convex side (Van de Kelft et al., 2012). According to this logic, the rate of abnormal screw placement should be higher on the concave side than on the convex side, regardless of the normal vertebral body. However, no statistical difference was found in our study. After analysis, the possible causes are as follows: ① The object of our study is congenital scoliosis. ② Compared with adolescent idiopathic scoliosis, the patients with congenital scoliosis were younger, and the vertebral body was not significantly affected by the degree of scoliosis. ③ The deformity was limited to the vertebral body with congenital malformation, and the vertebral pedicle hypoplasia was limited to the concave side of the vertebral body with abnormal morphology. This explains why there was no statistically significant difference in the accuracy of screw placement between concave and convex sides in our study. We should note that studies have found that the epidural space between the spinal cord and the vertebral body is generally less than 1mm on the concave side of scoliosis, while this distance is 3-5mm on the convex side (Liljenqvist et al., 2002). At the same time, the probability of abnormal screw placement on the concave side of the abnormal vertebral body is large, so the fault tolerance space is relatively small. Therefore, we should follow the principle of "better outside than inside" when placing screws on the concave side of the abnormal vertebral body, so as to avoid the screw being inserted into the spinal canal and causing occult injury to the spinal cord. A retrospective study of adult patients with scoliosis found that the accurate rate of screw placement was 93.8% using CT evaluation (Kim et al., 2004). However, a case study of pediatric scoliosis showed that the accuracy rate of pedicle screw placement was 89.5% (Lehman Jr et al., 2007). Studies have found that (Liu et al., 2016) the accuracy of free-hand screw placement is positively correlated with the diameter of pedicle screw. It is reasonable to expect that pedicle screw insertion becomes progressively less difficult with increasing age. Age is a factor affecting the placement of pedicle screws. The younger the age, the less mature the vertebral body and the smaller the pedicle. This increases the difficulty of screw placement and increases the rate of wall breakage. For the same individual, the lumbar pedicle is wider than the thoracic pedicle, which also reduces the difficulty of screw placement. Studies on electrical stimulation signals (Shi et al., 2003) have found that the thoracic pedicle is more prone to abnormal screw placement than the lumbar spine. Similarly, in a study of patients undergoing pedicle screw fixation for adult spinal disorders, it was found (Parker et al., 2011) that the thoracic spine was more prone to malplacement than the lumbar spine. Sarwahi et al. (Sarwahi, Sugarman, et al., 2014) analyzed the morphology of the pedicle of scoliosis and found that most of the abnormal pedicle was located in the thoracic spine, and most of them were in the upper thoracic spine. They suggested that the smaller size of the upper thoracic vertebral body might be responsible for this abnormality. The small vertebral body itself and the presence of deformity will increase the difficulty of pedicle screw placement, similar to what we said 1+1 > 2. The same applies to the case of the thoracolumbar spine in our study. Due to the smaller vertebral morphology of the thoracic spine and the more abnormal vertebral bodies in the thoracic spine than the lumbar spine in our study, the probability of abnormal screw placement in the thoracic spine is higher than that in the lumbar spine. Therefore, safety awareness should be improved during thoracic pedicle screw fixation. Accurate placement of pedicle screws can not only ensure safety but also provide adequate biological characteristics (Cho et al., 2010). But what is the exact definition, is it allowed within 2mm or 4mm? In a study of severe idiopathic scoliosis in adults and adolescents, the rate of malplacement of screws exceeding 2mm through the cortical bone was found to be 3.7% (Kuklo et al., 2005). It has also been found (Baghdadi et al., 2013; Heidenreich et al., 2015) that 9% of the screws in children who were placed by hand broke through the cortical bone more than 4mm. It can be seen that the conclusions obtained will also be affected by the different definition ranges of accuracy. But how to better limit this range, especially for children is more important. A literature study (Hicks et al., 2010) shows that it is acceptable for wall breakage to occur within 2mm. However, some scholars (Gertzbein & Robbins, 1990; Polly Jr et al., 2004) defined a safe zone within 4mm of the intraspinal breakthrough. However, these studies seem to ignore the consideration of the different locations of the broken wall. Several case studies (Alanay et al., 2003; Bekmez et al., 2018; Canavese et al., 2017; Fernandes et al., 2019; Jain et al., 2009) have reported that patients with poor screw placement that breaks through the medial or lateral wall develop corresponding neurological complications as the lateral curve progresses during growth and development. Of course, with the growth of the vertebral body, the protrusion degree of the screws breaking through the anterior wall of the vertebral body will decrease, so the adverse effects of the protruding screws on the human body will decrease (Faro et al., 2005). These are based on the location of the screw, for less than 4mm this range may be used to break through the lateral wall of the pedicle or the anterior wall of the vertebral body. However, for children with scoliosis and vertebral deformity, the screw breaking through the inner wall of the pedicle will migrate into the spinal canal with the growth and development of potential deformity. Studies have shown (Floccari et al., 2018) that children with a severe spinal deformity or congenital spinal deformity may have anatomical variations in the blood vessels of the spinal cord or congenital abnormalities in the development of the spinal cord. These make them less tolerant of medial protrusion of the pedicle. A more stringent "safe zone" (less than 2mm) may be more accurate and safe for children. We recommend that parents of children with medial wall breakthroughs in our study be followed up every 6 to 12 months so that they can receive timely intervention if corresponding neurologic symptoms occur. Considering that the abnormal screw placement is not only related to the size of the pedicle and vertebral body, we should also consider the thickness and length of the screw. The application of relatively short and thin pedicle screws may reduce the incidence of abnormal screw placement. However, the biomechanical efficiency will be greatly reduced. The screws we selected were relatively long. First, considering the firmness of fixation, and second, children are different from adults, especially for children with spinal deformity, and spinal deformity may be aggravated with the growth of the spine. Therefore, a relatively long pedicle screw can provide a higher holding force and fixation effect. The accuracy of pedicle screw placement is affected by many factors, but the different evaluation methods will also subjectively cause differences in the accuracy of pedicle screw placement. Studies (Harimaya et al., 2011; Ruf & Harms, 2002) have found that the risk of poor screw placement in children is less than 4% when an X-ray is used as a means of assessment. However, if CT was used as the evaluation index, the incidence of abnormal screw placement was 6.8% (Ranade et al., 2009). Another study showed that the rate of abnormal pedicle screw placement by postoperative CT evaluation was as high as 15.7% in patients with free-hand screw placement (Hicks et al., 2010). CT can more accurately evaluate the position and degree of screw protrusion than X-ray. However, the effects of radiation need to be considered. We also did not routinely perform postoperative CT but instead required abdominal or chest CT for other reasons. This is because studies (Mathews et al., 2013) have shown that for children and adolescents, the risk of cancer after receiving the same amount of radiation is higher than that for adults. Even with the latest low-dose CT, the incidence of cancer has not been reduced. While technology brings technological progress, some "side effects" cannot be ignored. In recent years, the application of intraoperative navigation technology is increasing, but it also faces the potential risks caused by CT radiation. Studies have found that the radiation dose of CT navigation in spinal surgery is 2.7 times higher than that of intraoperative X-ray fluoroscopy (Mendelsohn et al., 2016). We need to evaluate the advantages and disadvantages of a new technology before applying it. In addition to the consideration of the disadvantages brought by radiation, not all pediatric spine patients and all vertebral segments need to be operated on with the help of navigation. For determining the type of disease and which vertebral level has the highest probability of screw misplacement, clinicians can be provided with screw placement strategies, which is the optimal choice for navigation applications (Heidenreich et al., 2015). However, for regions and hospitals without intraoperative navigation equipment, understanding the high-risk segments and vertebral bodies of screw placement, reducing the density of pedicle screws and limiting the placement of screws in high-risk areas can statistically reduce the occurrence of screw misplacement (Shen et al., 2017), and can also effectively avoid the risk of poor screw placement. The last issue that cannot be ignored is wound healing. The subjects of our study were early-onset congenital scoliosis. On the one hand, the age of patients with this type of scoliosis is less than 10 years old, on the other hand, many patients may have eating problems and growth retardation due to the existence of deformities.

5. Conclusion

The findings of this study demonstrate that freehand thoracic and lumbar pedicle screw fixation in children with early-onset congenital scoliosis (ECS) achieves high accuracy, with 82.7% of screws correctly placed as assessed by postoperative computed tomography (CT) imaging. The remaining 17.3% of screws exhibited misplacement, with a higher incidence of abnormalities in the thoracic vertebrae and on the concave side of morphologically abnormal vertebrae. Despite these variations, no intraoperative or postoperative complications related to pedicle screw insertion were observed, confirming the overall safety and feasibility of this technique in young children.

5.1 Key Clinical Implications

1. Accuracy and Safety of Freehand Pedicle Screw Placement: The results confirm that freehand pedicle screw placement remains a reliable and effective technique for stabilizing the thoracic and lumbar spine in pediatric ECS patients. The high placement accuracy observed in this study suggests that experienced surgeons can achieve precise screw positioning without the need

for navigation-assisted systems, which may reduce surgical costs, minimize radiation exposure, and shorten operative time. However, given the higher rate of misplacement in thoracic vertebrae and morphologically abnormal vertebrae, particular caution should be exercised when inserting screws in these regions.

2. Risk Factors for Pedicle Screw Misplacement: The study highlights key risk factors associated with pedicle screw misplacement, including:

- Thoracic vertebrae having a significantly higher misplacement rate than lumbar vertebrae due to their smaller pedicles and increased anatomical variability.
- Morphologically abnormal vertebrae, especially those affected by congenital malformations, posing challenges for proper screw trajectory.
- Concave side screw placements exhibiting a significantly higher misplacement rate compared to the convex side, indicating the need for refined surgical techniques in these areas.

These findings emphasize the importance of preoperative planning, meticulous intraoperative techniques, and the use of anatomical landmarks to improve placement precision, particularly in high-risk regions.

3. Implications for Postoperative Recovery and Physical Rehabilitation: The accuracy of pedicle screw placement has a direct impact on postoperative spinal stability, early rehabilitation, and functional mobility. Precise screw positioning ensures optimal biomechanical support, reducing the risk of implant failure, neurological complications, and subsequent corrective surgeries. As ECS patients often require long-term rehabilitation to regain spinal flexibility and strength, proper screw placement facilitates early mobilization, postural correction, and improved physical function. Moreover, accurate pedicle screw fixation contributes to better long-term spinal alignment, which is critical for preventing secondary deformities and enabling children to participate in physical activities, sports, and daily movement without significant restrictions. Therefore, enhancing pedicle screw accuracy through surgical skill refinement and improved intraoperative guidance techniques can significantly improve rehabilitation outcomes and quality of life for pediatric scoliosis patients.

5.2 Future Directions and Recommendations

While this study provides valuable insights into the accuracy and safety of freehand pedicle screw placement in ECS patients, several areas require further investigation:

1. Longitudinal Follow-Up Studies: Future research should focus on the long-term outcomes of pedicle screw placement, assessing its effects on

spinal growth, correction durability, and functional mobility.

2. Advanced Surgical Techniques: The integration of 3D-printed spinal models, intraoperative navigation, and robotic-assisted systems could be explored to enhance precision in high-risk vertebrae.

3. Postoperative Rehabilitation Strategies: Studies evaluating the impact of early physical therapy and rehabilitation protocols on spinal function and muscle adaptation in ECS patients could provide deeper insights into optimizing recovery.

4. Comparative Analysis with Navigation-Assisted Techniques: A comparative study between freehand and navigation-assisted pedicle screw placement could help determine the most effective technique for pediatric spinal stabilization.

5.3 Conclusion Summary

In conclusion, freehand pedicle screw fixation in early-onset congenital scoliosis patients demonstrates high accuracy and a favourable safety profile, making it a viable technique for pediatric spinal stabilization. However, special attention must be given to thoracic vertebrae, morphologically abnormal vertebrae, and concave-side placements, where misplacement rates are higher. The study underscores the clinical significance of precise pedicle screw placement in improving spinal stability, reducing complications, and supporting effective postoperative rehabilitation. By refining surgical techniques and incorporating innovative technologies, surgeons can further enhance placement accuracy, optimize patient recovery, and improve long-term functional outcomes for children undergoing scoliosis correction surgery.

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