Article

Anatomical Feasibility and Morphometric Analysis of Cortical Bone Trajectory Screw Fixation in the Pediatric Lumbar Spine Using Computed Tomography

Ann. Ital. Chir., 2026 97, 7: 1172–1181
https://doi.org/10.62713/aic.4529

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AIM: The cortical bone trajectory (CBT) screw fixation technique has been widely adopted in adult spinal surgery due to its minimally invasive nature and biomechanical advantages. However, systematic research on its anatomical feasibility and morphometric parameters in the pediatric lumbar spine remains lacking. This study aimed to evaluate the anatomical feasibility of CBT screw fixation in the pediatric lumbar spine, and to characterize the variations in screw dimensions and insertion angles across different age groups and lumbar levels, providing an individualized reference for pediatric lumbar surgery.
METHODS: This retrospective study included 80 pediatric patients aged 5–16 years without lumbar pathologies. Participants were stratified into four age groups (5–7, 8–10, 11–13, and 14–16 years, denoted as Groups 1, 2, 3, and 4, respectively), with 20 patients per group and sex-matched distribution (10 males and 10 females per group). Multiplanar reconstruction based on computed tomography (CT) images with 1 mm reconstruction was performed to measure the following parameters at each lumbar level (L1–L5): maximum screw length (MSL), maximum screw diameter (MSD), lateral angle (LA), and cephalad angle (CA). Statistical analysis was conducted using a mixed linear effects model to assess the influence of age, sex, lumbar level, and their interactions on each parameter, supplemented by analysis of variance (ANOVA) and post hoc multiple comparisons with Bonferroni correction.
RESULTS: MSL increased significantly with age and showed a level-specific pattern, generally rising from L1 to L3 and declining at L5. In the mixed-effects model, age group and lumbar level had significant effects on MSL, and a significant Group 4 × female interaction was observed. MSD increased progressively from L1 to L5 and was significantly affected by age group, sex, lumbar level, and age × sex interaction, with a particularly significant Group 2 × female interaction (estimate = 0.459, $p < 0.001$). LA generally increased with age and caudal progression of the lumbar level and was significantly influenced by age group, sex, and lumbar level. In contrast, CA decreased progressively from L1 to L5 within each age group and was significantly influenced by age group and lumbar level, whereas the age × sex interaction was not significant. Anatomical feasibility was assessed using a screw diameter threshold of $\geq$ 4.5 mm. The applicability rate of CBT fixation increased with both age and caudal lumbar level, with lower feasibility mainly observed at upper lumbar levels in younger children. At L1, applicability rates were 50% in Group 1, 70% in Group 2, and 100% in Groups 3 and 4; at L5, applicability reached 100% in all groups.
CONCLUSIONS: The anatomical parameters for CBT screw placement in the pediatric lumbar spine are significantly influenced by age, lumbar level, and sex. This study provides a systematic anatomical reference for CBT screw dimensions and trajectory angles across pediatric age groups. Anatomical feasibility, defined by a $\geq$4.5 mm screw diameter threshold, was higher in older children, whereas the use in younger children requires careful individual evaluation due to limited space and increased risk of cortical disruption, especially at upper lumbar levels. These findings offer supportive evidence for guiding patient selection and preoperative planning, though clinical applicability requires further biomechanical and outcome validation.

Keywords: cortical bone trajectory; minimally invasive technique; computed tomography; pediatric lumbar spine

Introduction

The pedicle screw fixation system has been widely used in spinal surgery owing to its fundamental biomechanical advantage of three-column control [1–4]. However, pedicle screw placement is not without limitations, such as susceptibility to neurovascular injury and a requirement for significant muscle dissection to expose bone landmarks for safe insertion of pedicle screws, especially for caudal lumbar fixation. To address these limitations, minimally inva-

Submitted: 7 January 2026 Revised: 23 March 2026 Accepted: 22 April 2026 Published: 14 July 2026
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Editor: Roberto Gazzeri

sive spine surgery (MIS) has been developed and has now emerged as a core developmental direction in spinal surgery in recent years. Relevant clinical research [5] has confirmed that by reducing soft tissue injury, MIS confers distinct advantages over traditional open surgery in terms of clinical efficacy and safety. It can optimize intraoperative blood loss, drainage volume and surgical duration, while improving postoperative pain relief and functional recovery, reducing the incidence of complications, and exerting no adverse effects on spinal stability and morphology. Building on the remarkable clinical advantages demonstrated by MIS techniques, Matsukawa *et al*. [6] introduced the cortical bone trajectory (CBT) technique for lumbar pedicle screw fixation. This approach follows a caudocephalad trajectory in the sagittal plane and a lateral trajectory in the transverse plane, maximizing engagement with cortical bone from the pedicle to the vertebral body.

Biomechanical studies have reported a 30% increase in uniaxial yield pullout load and equivalency in mixed loading as compared with the traditional pedicle screw fixation [6,7]. In addition, the screw insertion through a medial entry point enables less tissue dissection and retraction for reduced muscle disruption, which is primarily advantageous in the lower lumbar spine, where the traditional pedicle screw fixation requires more lateral exposure. Furthermore, Matsukawa *et al*. [8] reported a facet joint violation rate of 11.8% associated with CBT pedicle screw placement, with no cases of intra-articular violation. This rate is relatively low compared with those reported in the literature.

To the best of our knowledge, no previous reports have described the CBT technique used in the pediatric lumbar spine. Therefore, this study aims to assess the feasibility of CBT screw insertion in the pediatric lumbar spine and to define optimal screw size and trajectory orientations based on computed tomography (CT).

Methods

Study Population

This study was approved by the Ethics Committee of Jinhua Municipal Central Hospital (2018-117). In this retrospective study, pediatric patients who underwent abdominal CT scans for non-spinal-related conditions (e.g., abdominal pain, abdominal mass, trauma evaluation) at Jinhua Municipal Central Hospital between January 2018 and December 2024 were recruited. Patients were excluded if they had lumbar spine deformities, trauma, tumors, infections, or a history of previous spinal surgery.

Stratified sampling was used for case selection, with patients divided into four age groups. Sex matching was conducted in each group to balance potential confounding factors, and a total of 80 patients were finally enrolled. The sample was categorized into four groups according to age ranges, as follows: Group 1 (5–7 years old); Group 2 (8–10 years old); Group 3 (11–13 years old); and Group 4 (14–16 years old). Each group comprised 20 subjects with an equal sex distribution.

CT Scanning and Image Reconstruction

Abdominal CT scans were performed using a Philips Brilliance iCT 256-slice CT scanner (Philips Medical Systems, Eindhoven, Netherlands). To ensure complete coverage of the lumbar spine for morphological measurement, the scanning range was specifically set to extend from the diaphragm to the pelvic cavity, which consistently encompasses the entire L1–L5 vertebral segments. The original data were acquired with a slice thickness of 5 mm. Scan parameters were as follows: tube voltage of 120 kV, tube current of 180 mA, a 512 × 512 matrix, collimation of 128 × 0.625 mm, pitch of 0.6, DoseRight Z-DOM, and 250 mAs per slice. The raw data were subsequently reconstructed into images with a slice thickness of 1 mm and then imported into the EBW workstation for two-dimensional multiplanar reconstruction.

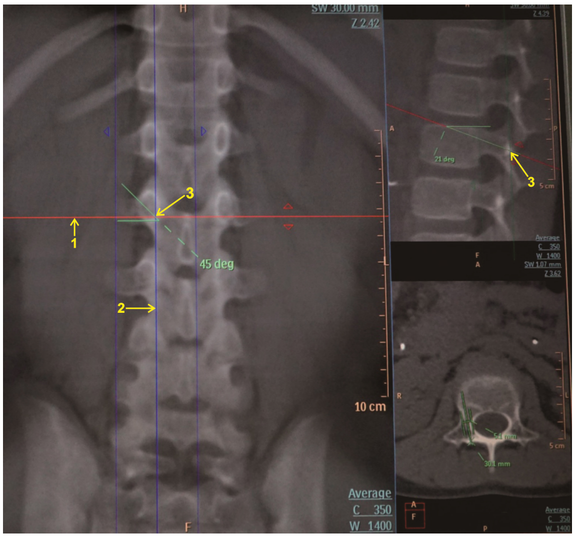

Fig. 1. Determination of the starting point for cortical bone trajectory screw placement. Notes: 1, the red line was the horizontal axis, which can be used to calibrate the axial plane; 2, the blue line was the sagittal axis, which was used to adjust the sagittal plane; 3, the screw insertion point was located in the 5 o'clock orientation of the pedicle. The orientation markers on the CT workstation indicate anatomical directions: A, anterior; P, posterior; F, foot/inferior; H, head/superior.

Measurement Methods

First, the coronal plane slice thickness was increased to clearly delineate the pedicle projection. The horizontal and sagittal axes were subsequently repositioned to align with the inferior and medial margins of the pedicle projection, respectively. A 45° angle was plotted such that its extension line overlapped with the pedicle projection; the intersection between this line and the pedicle contour was identified as the screw starting point (Fig. 1). Subsequently, the sagittal plane slice thickness was enhanced, and the horizontal axis was adjusted to coincide with the anatomical axis of the pedicle, thereby reconstructing a corresponding axial plane. Finally, the following parameters were recorded: (1) maximal screw length (MSL), (2) maximal screw diameter (MSD), (3) lateral angle (LA), and (4) cephalad angle (CA) (Figs. 2,3).

All imaging parameters were independently measured by two experienced observers in spinal imaging analysis. Measurements were performed in a blinded manner, with the observers unaware of the patient group allocation. Each parameter was measured in triplicate by each observer, and the mean of their measurements was used for final analysis. Both bilateral pedicles were included in the measurement, and the average of the left and right measurements was adopted as the representative value for each segment in the statistical analysis.

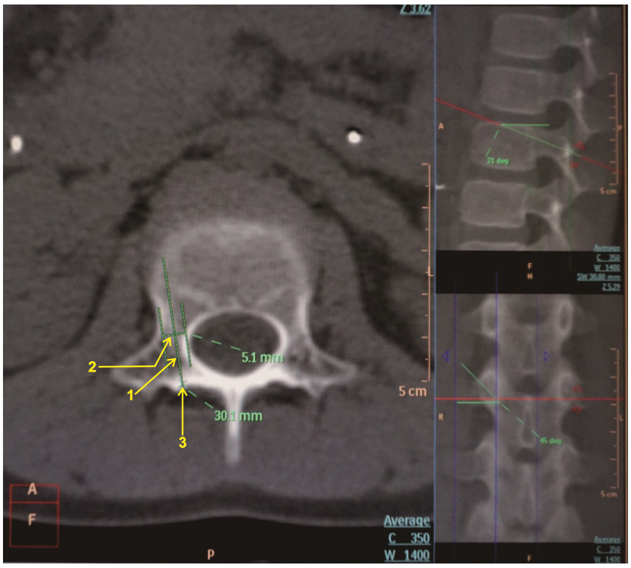

Fig. 2. Measurement of maximal screw length and diameter along the cortical bone trajectory. Notes: 1, maximal screw length; 2, maximal screw diameter; 3, screw insertion point.

Statistical Analysis

Statistical analysis was performed using SPSS version 22.0 (IBM Corp., Armonk, NY, USA) and R software (R Foundation for Statistical Computing, Vienna, Austria). Continuous variables are expressed as mean ± standard deviation. To assess the effects of age group, sex, lumbar level, and their interactions on screw parameters, linear mixed-effects models were established for MSL, MSD, LA, and CA, with patient identity included as a random intercept. Fixed effects comprised age group, sex, lumbar level, and their two-way interactions. Post hoc pairwise comparisons were conducted using the Bonferroni method. Effect sizes were expressed as partial η^2 and interpreted according to conventional criteria (small $\geq$0.01, medium $\geq$0.06, large $\geq$0.14). The significance level was set at $\alpha = 0.05$.

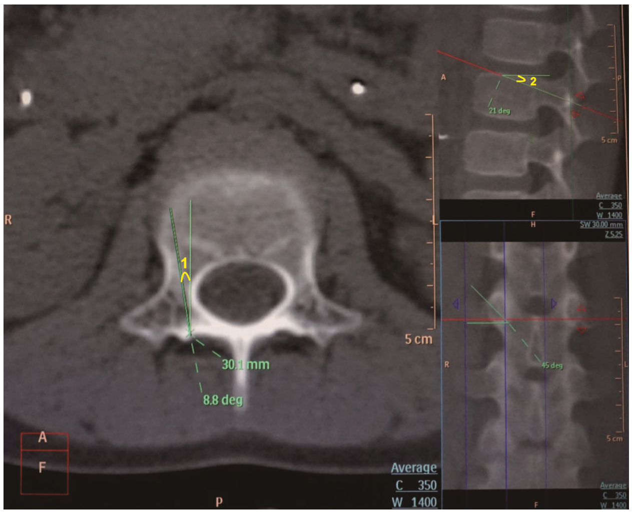

Fig. 3. Measurement of the lateral and cephalad angles for cortical bone trajectory screw placement. Notes: 1, lateral angle; 2, cephalad angle.

Results

Maximal Screw Length

The mean values and standard deviations for MSL are presented in Table 1. Fig. 4A illustrates the mean MSL values across lumbar levels, from L1 to L5, for each age group. With increasing age, MSL showed a significant increase. Across all age groups, MSL generally increased from L1 to L3, reaching the maximum value at L3, and then decreased from L4 to L5. In the linear mixed-effects model, MSL was significantly greater in Groups 2, 3, and 4 than in Group 1 (all $p < 0.001$; **Supplementary Table 1**). Compared with L1, MSL was significantly longer at L2 and L3 and significantly shorter at L5 ($p < 0.001$), whereas the difference at L4 did not reach statistical significance. The coefficient for female sex at the reference category was negative but not statistically significant (estimate = –0.62, $p = 0.070$). However, a significant Group 4 × female interaction was observed (estimate = –2.04, $p < 0.001$), indicating that the sex-related reduction in MSL was more pronounced in the 14–16 year age group than in the 5–7 year reference group. Taken together, these findings suggest that MSL variation reflects combined age-related, lumbar-level-specific, and sex-related effects rather than being attributable to a single determinant.

Maximal Screw Diameter

The mean values and standard deviations for MSD are presented in Table 2. Fig. 4B illustrates that MSD progressively and significantly increased from L1 to L5 across all age groups. MSD was significantly influenced by age, lum-

Table 1. Maximal screw length.

Level		Group 1	Group 2	Group 3	Group 4
L1	Male	25.92 ± 1.12	28.63 ± 1.19	32.05 ± 1.64	34.64 ± 2.01
	Female	25.59 ± 1.34	26.95 ± 1.50	30.50 ± 0.88	32.11 ± 1.62
	All	25.76 ± 1.21	27.79 ± 1.57	31.28 ± 1.51	33.38 ± 2.20
L2	Male	27.39 ± 0.73	29.97 ± 0.77	33.15 ± 1.48	36.42 ± 1.78
	Female	26.84 ± 1.45	28.32 ± 1.70	31.52 ± 0.98	33.74 ± 1.68
	All	27.12 ± 1.15	29.15 ± 1.54	32.34 ± 1.48	35.08 ± 2.17
L3	Male	28.37 ± 0.76	31.22 ± 1.02	33.88 ± 1.63	37.59 ± 2.01
	Female	27.61 ± 1.36	29.92 ± 1.67	32.49 ± 1.01	35.13 ± 1.60
	All	27.99 ± 1.14	30.57 ± 1.51	33.19 ± 1.50	36.36 ± 2.17
L4	Male	26.57 ± 0.42	28.38 ± 1.14	31.79 ± 2.26	35.68 ± 3.32
	Female	26.07 ± 0.60	27.59 ± 1.29	30.55 ± 1.42	32.80 ± 1.68
	All	26.32 ± 0.57	27.94 ± 1.27	31.17 ± 1.95	34.24 ± 2.96
L5	Male	25.03 ± 0.70	26.12 ± 0.61	29.47 ± 2.39	33.07 ± 2.94
	Female	23.54 ± 1.92	25.53 ± 0.62	27.66 ± 1.70	29.88 ± 1.94
	All	24.29 ± 1.60	25.83 ± 0.67	28.57 ± 2.22	31.48 ± 2.92

Notes: Group 1, 5–7 years; Group 2, 8–10 years; Group 3, 11–13 years; Group 4, 14–16 years. All data are measured in millimeters (mm) and expressed as mean ± SD.

bar level, and their interaction with sex (**Supplementary Table 2**). The main effect of age group was significant, with Groups 3 and 4 showing a notable increase in MSD compared to Group 1 (estimates = 0.762 and 1.383, respectively, $p < 0.001$). A significant main effect of sex indicated that females had a consistently smaller MSD than males ($p < 0.001$). The age × sex interaction was particularly pronounced in Group 2 (estimate = 0.459, $p < 0.001$), suggesting a more marked sex-specific variation in this age range, while no significant interaction was observed in Group 3 ($p = 0.099$) or Group 4 ($p = 0.336$).

Lateral Angle

The mean values and standard deviations for LA are presented in Table 3. Fig. 4C shows the mean LA values from L1 to L5 for each age group. LA progressively increased from L1 to L5 across all age groups. Notably, LA increased significantly from L1 to L3 and from L4 to L5. LA was significantly influenced by age, sex, and lumbar level (**Supplementary Table 3**). The main effect of age group was significant, with Groups 2, 3, and 4 showing significantly greater LA compared to Group 1 ($p < 0.01$). A significant main effect of sex indicated that females had consistently smaller LA than males (estimate = –0.686, $p < 0.001$).

Cephalad Angle

The mean values and standard deviations for CA are presented in Table 4. Fig. 4D displays the mean CA values at each lumbar level across the four age groups. CA progressively and significantly decreased from L1 to L5 across all age groups. Notably, Group 3 exhibited higher mean CA values than Group 4 at all lumbar levels except L1, despite the overall age-related increasing trend. The CA was significantly influenced by age group and lumbar level (**Supplementary Table 4**). The main effect of sex did not reach statistical significance, and the age × sex interaction was not significant in any group ($p > 0.05$).

Statistical Validation of Model Effects

To further validate the statistical significance of the observed effects, we conducted a comprehensive analysis of variance (ANOVA) for all main effects and interactions (**Supplementary Table 5**). The results confirmed significant main effects of age group, sex, and lumbar level on all four outcome variables (all $p < 0.001$). The age × sex interaction was significant for MSL ($F = 6.63$, $p < 0.001$) and MSD ($F = 6.29$, $p < 0.001$), but not for LA ($F = 2.50$, $p = 0.067$) or CA ($F = 1.94$, $p = 0.132$). Post hoc pairwise comparisons revealed significant differences between most age groups for MSL, MSD, and LA (**Supplementary Table 6**). However, CA showed no significant differences between Group 1 and Group 2, Group 1 and Group 4, Group 2 and Group 4, as well as Group 3 and Group 4. Additionally, for MSL, the sex difference was non-significant in Group 2 ($p = 0.246$) and Group 3 ($p = 0.097$), with significant divergence emerging only in Group 4 ($p < 0.001$), suggesting a trend toward sex differences from early adolescence onward.

Application Rates of CBT Technique Across Lumbar Levels in Different Age Groups

Fig. 5 illustrates the anatomical feasibility of CBT screw fixation based on MSD, using a threshold of ≥4.5 mm. Application rates across lumbar levels L1–L5 are presented for each age group. At L1, feasibility was 50% in Group 1,

Table 2. Maximal screw diameter.

Level		Group 1	Group 2	Group 3	Group 4
L1	Male	4.68 ± 0.23	4.74 ± 0.35	5.41 ± 0.22	5.92 ± 0.46
	Female	4.01 ± 0.48	4.58 ± 0.24	5.02 ± 0.17	5.42 ± 0.29
	All	4.35 ± 0.50	4.66 ± 0.30	5.22 ± 0.28	5.67 ± 0.45
L2	Male	4.92 ± 0.21	5.02 ± 0.34	5.65 ± 0.28	6.28 ± 0.48
	Female	4.33 ± 0.38	4.92 ± 0.23	5.25 ± 0.21	5.78 ± 0.27
	All	4.63 ± 0.43	4.97 ± 0.28	5.45 ± 0.32	6.03 ± 0.46
L3	Male	5.20 ± 0.27	5.39 ± 0.46	6.10 ± 0.36	6.70 ± 0.58
	Female	4.58 ± 0.37	5.28 ± 0.35	5.58 ± 0.26	6.19 ± 0.31
	All	4.89 ± 0.45	5.34 ± 0.40	5.84 ± 0.41	6.45 ± 0.52
L4	Male	5.48 ± 0.28	5.74 ± 0.48	6.30 ± 0.38	7.08 ± 0.59
	Female	4.83 ± 0.35	5.68 ± 0.24	5.92 ± 0.23	6.55 ± 0.37
	All	5.16 ± 0.45	5.71 ± 0.37	6.11 ± 0.36	6.82 ± 0.55
L5	Male	5.75 ± 0.26	6.07 ± 0.40	6.71 ± 0.53	7.47 ± 0.83
	Female	5.22 ± 0.32	5.99 ± 0.12	6.34 ± 0.32	7.05 ± 0.42
	All	5.49 ± 0.39	6.03 ± 0.29	6.53 ± 0.47	7.26 ± 0.67

Notes: Group 1, 5–7 years; Group 2, 8–10 years; Group 3, 11–13 years; Group 4, 14–16 years. All data are measured in millimeters (mm) and expressed as mean ± SD.

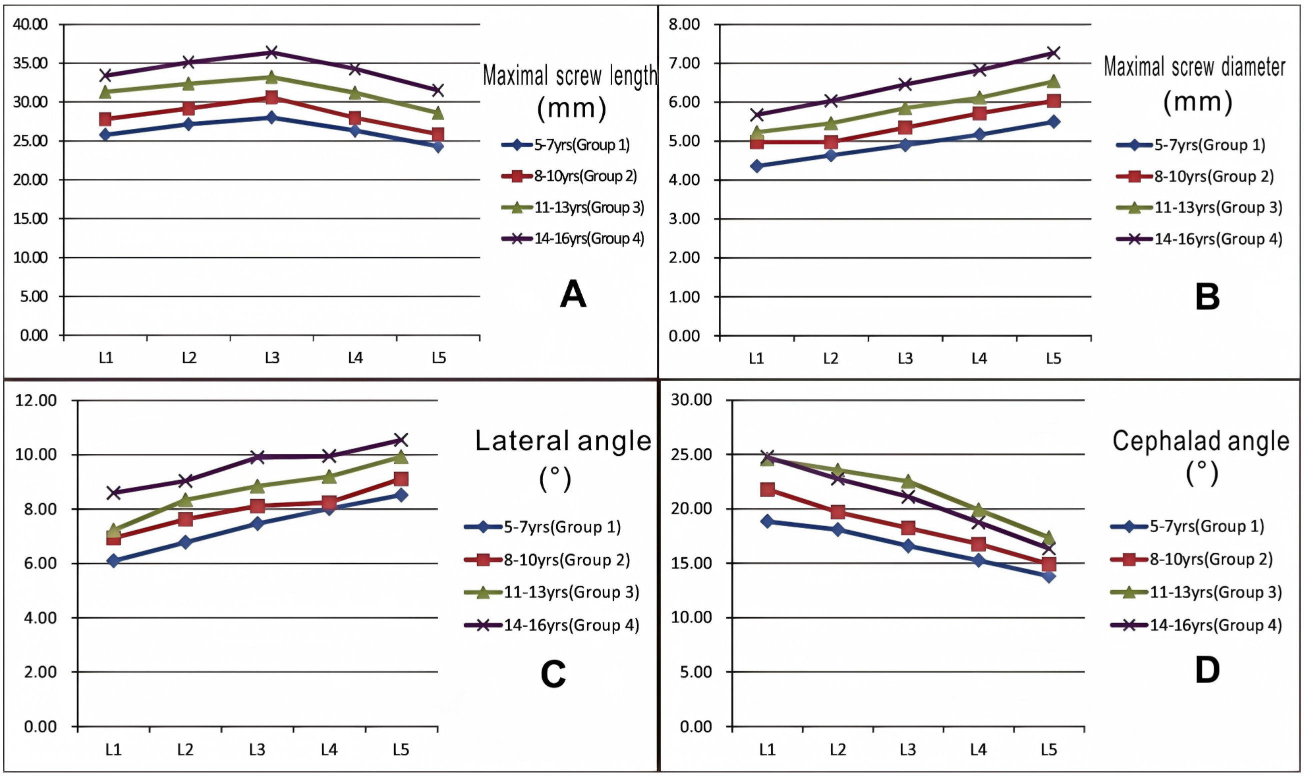

Fig. 4. Graphs illustrating mean values of lumbar cortical bone trajectory (CBT) screw parameters in pediatric patients from lumbar level L1 to L5 across different age groups. (A) maximal screw length (MSL), (B) maximal screw diameter (MSD), (C) lateral angle (LA), and (D) cephalad angle (CA).

70% in Group 2, and 100% in both Groups 3 and 4. Within Group 1, feasibility progressively increased from 50% at L1 to 100% at L5. Across all age groups, feasibility improved from L1 to L5, with the most pronounced increment observed in younger children.

Discussion

King [9] was the first to introduce facet screw placement for the treatment of degenerative lumbar conditions and, in 1948, also explored the possibility of achieving three-dimensional spinal fixation through the pedicle. In 1959,

Table 3. Lateral angle.

Level		Group 1	Group 2	Group 3	Group 4
L1	Male	6.47 ± 1.02	7.18 ± 0.56	8.06 ± 0.25	8.75 ± 0.50
	Female	5.71 ± 0.86	6.67 ± 0.60	7.92 ± 0.31	8.43 ± 0.20
	All	6.09 ± 1.00	6.93 ± 0.62	7.99 ± 0.28	8.59 ± 0.41
L2	Male	7.16 ± 0.78	7.76 ± 0.49	8.40 ± 0.49	9.08 ± 0.84
	Female	6.37 ± 0.96	7.48 ± 0.66	8.25 ± 0.38	8.97 ± 0.27
	All	6.77 ± 0.94	7.62 ± 0.58	8.33 ± 0.44	9.03 ± 0.60
L3	Male	7.85 ± 0.50	8.23 ± 0.53	8.96 ± 0.50	9.62 ± 0.71
	Female	7.07 ± 0.84	7.98 ± 0.57	8.72 ± 0.38	9.38 ± 0.30
	All	7.46 ± 0.78	8.11 ± 0.56	8.84 ± 0.45	9.50 ± 0.54
L4	Male	8.31 ± 0.38	8.71 ± 0.49	9.25 ± 0.77	10.05 ± 0.90
	Female	7.71 ± 0.66	7.77 ± 0.74	9.12 ± 0.34	9.85 ± 0.39
	All	8.01 ± 0.61	8.24 ± 0.98	9.19 ± 0.58	9.95 ± 0.68
L5	Male	8.78 ± 0.26	9.24 ± 0.53	10.23 ± 0.47	10.73 ± 1.33
	Female	8.23 ± 0.48	8.97 ± 0.23	9.60 ± 0.37	10.35 ± 0.42
	All	8.51 ± 0.47	9.11 ± 0.42	9.92 ± 0.52	10.54 ± 0.98

Notes: Group 1, 5–7 years; Group 2, 8–10 years; Group 3, 11–13 years; Group 4, 14–16 years. All data are measured in degrees (°) and expressed as mean ± SD.

Table 4. Cephalad angle.

Level		Group 1	Group 2	Group 3	Group 4
L1	Male	19.65 ± 2.29	23.34 ± 2.01	25.23 ± 1.88	25.54 ± 3.33
	Female	18.00 ± 2.47	20.21 ± 2.61	23.90 ± 3.11	23.95 ± 2.36
	All	18.83 ± 2.47	21.78 ± 2.78	24.57 ± 2.59	24.75 ± 2.92
L2	Male	18.28 ± 1.97	20.71 ± 1.89	23.59 ± 2.42	23.92 ± 3.26
	Female	17.87 ± 4.34	18.66 ± 2.48	23.48 ± 2.75	21.57 ± 1.47
	All	18.08 ± 3.28	19.69 ± 2.39	23.54 ± 2.52	22.75 ± 2.74
L3	Male	17.16 ± 1.69	19.05 ± 1.55	22.61 ± 2.65	22.20 ± 2.59
	Female	15.97 ± 1.92	17.41 ± 2.33	22.40 ± 3.74	20.20 ± 1.49
	All	16.57 ± 1.86	18.23 ± 2.11	22.51 ± 3.15	21.10 ± 2.30
L4	Male	15.67 ± 1.23	17.77 ± 1.54	20.18 ± 1.96	19.54 ± 1.83
	Female	14.80 ± 1.96	15.73 ± 1.90	19.59 ± 2.58	17.94 ± 1.94
	All	15.24 ± 1.66	16.75 ± 1.98	19.89 ± 2.25	18.74 ± 2.01
L5	Male	14.28 ± 1.18	16.15 ± 1.22	17.66 ± 3.79	17.01 ± 2.48
	Female	13.30 ± 1.75	13.63 ± 1.64	16.99 ± 3.26	15.64 ± 1.62
	All	13.79 ± 1.54	14.89 ± 1.91	17.33 ± 3.46	16.33 ± 2.16

Notes: Group 1, 5–7 years; Group 2, 8–10 years; Group 3, 11–13 years; Group 4, 14–16 years. All data are measured in degrees (°) and expressed as mean ± SD.

Boucher [10] was widely credited with the first use of pedicle screws in North America; however, his description was more consistent with a longer facet screw that occasionally obtained oblique purchase across the pedicle. In 1969, Harrington and Tullos [11] attempted pedicle screw placement via the isthmus of the pedicle. Since then, pedicle screw instrumentation has been widely accepted as an efficient method of rigid fixation in the lumbosacral spine. Currently, transpedicular screw fixation of spinal segments has been applied across a broad range of surgical indications, including fractures [12,13], tumors [14,15], adolescent idiopathic scoliosis, and kyphotic deformities [3,4,16].

At the same time, numerous studies have reported the safety of pedicle screw fixation for various spinal disorders in pediatric patients. Ruf and Harms [17] studied the effectiveness and safety of pedicle screw fixation in young children and also assessed the effect of pedicle screw placement on further vertebral growth. They demonstrated that pedicle screw fixation can be performed safely in 1- and 2-year-old children without triggering adverse effects on vertebral development [17]. Ledonio *et al*. [18] reported that the accuracy of pedicle screw placement in the pediatric spine exceeded that reported in adults and was significantly more effective for scoliosis correction. Fujimori *et al*. [19] also investigated the safety of pedicle screws and constructs for

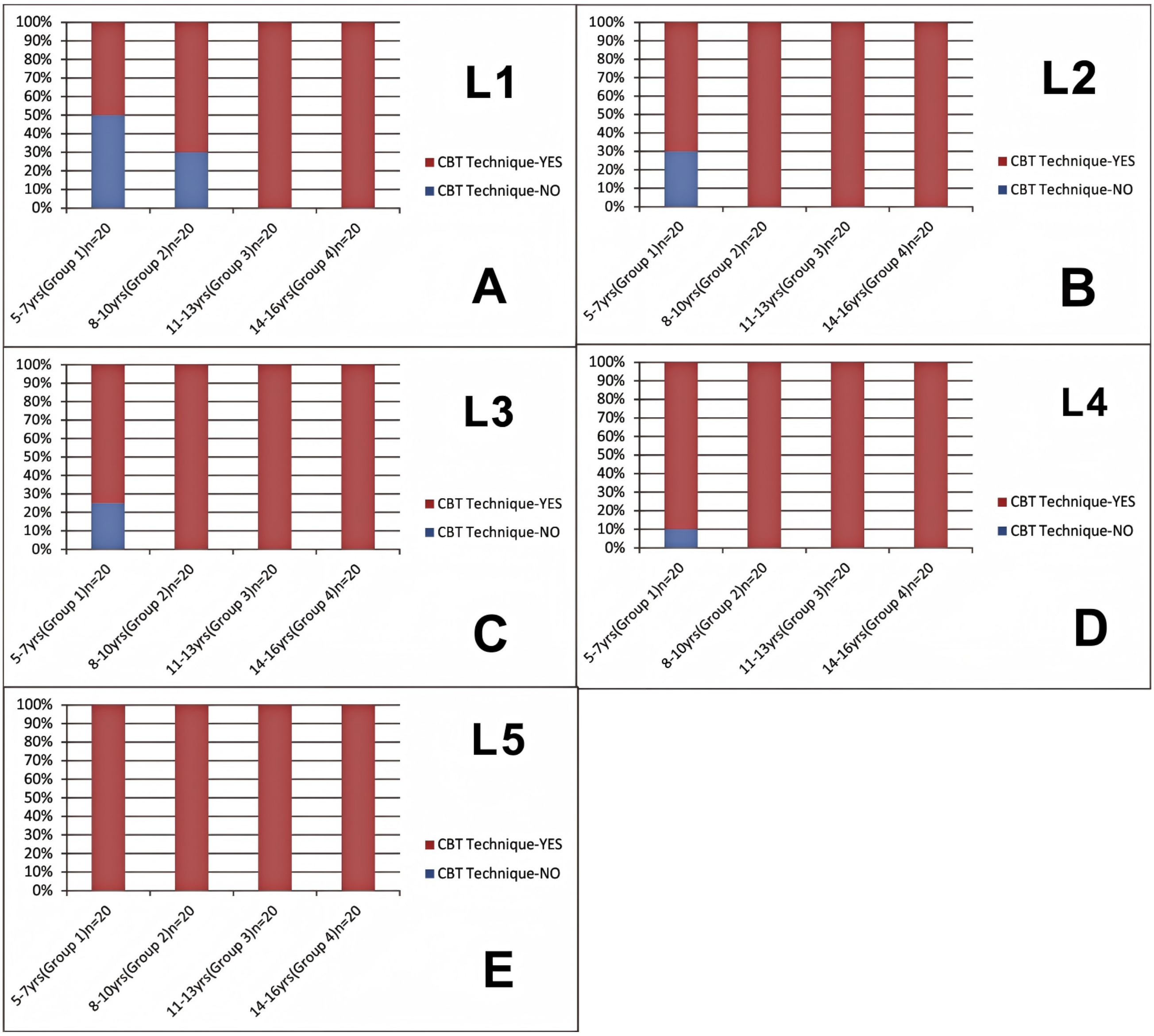

Fig. 5. Bar charts illustrating the percentage of patients suitable for 4.5-mm-diameter CBT screws across lumbar segments. (A–E) show the application rates of CBT screw fixation at lumbar levels L1, L2, L3, L4, and L5, respectively, based on a maximal screw diameter threshold of ≥4.5 mm.

pediatric patients, and found that overall complication rates associated with pedicle screws were 2.1% per patient and 0.14% per screw. Based on these findings, they concluded that pedicle screws can be used for infantile or juvenile patients, although complication rates associated with pedicle screws tended to be slightly higher in the younger groups.

However, traditional pedicle screw fixation is not without limitations, as it requires extensive muscle dissection to expose bony landmarks for pedicle screw placement, thereby increasing the risk of neurovascular injury, especially in caudal lumbar and sacral pedicle fixation. On the contrary, the CBT technique can enable less tissue dissection and retraction for reduced muscle disruption and also decrease the risk of neurovascular injury. In addition, several authors have reported that conventional pedicle screw instrumentation may increase the incidence of facet joint violation. Shah *et al*. [20] investigated the incidence of adjacent superior segment facet joint violation following transpedicular instrumentation in the lumbar spine and reported that facet joint violation detected through CT scans occurred in 20% of the screws and 32% of the patients. Chen *et al*. [21] demonstrated that superior segment facet joint violation occurred in all of the patients and involved all top-level screws when using Roy–Camille's technique. They further reported a facet joint violation rate of 23.8% of the screws and 32.9% of the patients with Weinstein's method. In spinal surgery, the optimization of surgical techniques has consistently focused on balancing therapeutic efficacy with the extent of surgical trauma. Systematic reviews have demonstrated that minimally invasive spinal surgery yields superior pain relief compared with open surgery, along with benefits such as shorter hospital stay and faster postoperative recovery, which are more aligned with the physiological characteristics and clinical needs of young patients [22]. This finding indicates that exploring a technical approach that integrates minimal invasiveness with therapeutic effectiveness holds important clinical value for pediatric lumbar fusion surgery. As a representative minimally invasive fixation technique, the CBT technique minimizes soft tissue dissection and retraction by optimizing the screw insertion path, thereby reducing the extent of muscular injury and the risk of neurovascular damage. A study by Matsukawa *et al*. [8] demonstrated that the incidence of facet joint injury caused by the CBT technique was only 11.8%, with no intra-articular injuries observed, which is significantly lower than that reported for the traditional pedicle screw technique. Additionally, the CBT technique utilizes shorter and smaller-diameter screws than conventional pedicle screws, maximizing the contact area between the screw threads and the high-density cortical bone and thereby further enhancing the stability of spinal fixation [7].

According to the above-mentioned defects, we evaluated the anatomical feasibility of the lumbar CBT technique in pediatric patients based on CT morphometric analysis. Measurements of our study suggested that maximal screw length increased from L1 to L3 in all groups, and it also increased from Group 1 (25.76 mm at L1, 27.12 mm at L2, 27.99 mm at L3) to Group 4 (33.38 mm at L1, 35.08 mm at L2, 36.36 mm at L3). However, maximal screw length decreased from L4 (26.32 mm in Group 1, 27.94 mm in Group 2, 31.17 mm in Group 3, 34.24 mm in Group 4) to L5 (24.29 mm in Group 1, 25.83 mm in Group 2, 28.57 mm in Group 3, 31.48 mm in Group 4) in all groups. Maximal screw diameter increased from L1 (4.35 mm in Group 1, 4.66 mm in Group 2, 5.22 mm in Group 3, 5.67 mm in Group 4) to L5 (5.49 mm in Group 1, 6.03 mm in Group 2, 6.53 mm in Group 3, 7.26 mm in Group 4), and showed an increment from Group 1 to Group 4. In pediatric lumbar segments, the lateral angle tended to increase with cephalad-to-caudal progression; however, the cephalad angle decreased from L1 to L5. Several biomechanical studies have shown that lumbar CBT screws with diameters of 4.5–5.5 mm can provide greater fixation strength than traditional screws [23–27]. In the present study, we used 4.5 mm as a reference threshold to assess anatomical feasibility in the pediatric population. In the 5–7 years age group (Group 1), our data indicated that the CBT technique was unsuitable for nearly 50% of the patients at the L1 segment, 30% at L2, 25% at L3, and 10% at L4. For the 8–10-year age group (Group 2), the proportion of patients in whom the CBT technique was not applicable was 30% at L1, while the technique was deemed suitable for all other lumbar segments in this group. Additionally, the CBT technique was applicable for every lumbar segment in both the 11–13 years (Group 3) and 14–16 years (Group 4) age groups. These findings align with the established adult anatomical benchmarks, where the transverse and sagittal trajectory angulations for CBT are reported to be approximately 25–30° and 10–16°, respectively [28]. However, the pediatric lumbar spine exhibits distinct developmental characteristics: our quantitative data confirmed that young children (5–10 years) have relatively limited maximal screw diameter at upper lumbar levels (L1–L2) compared to older children (11–16 years), which directly leads to lower anatomical feasibility of CBT screw fixation at these levels. Although bone mineral density (BMD) is a primary determinant of screw pullout strength in adult and osteoporotic models [29], pediatric BMD data were not available in this study. Thus, our morphometric findings can only confirm the anatomical feasibility of CBT screw placement in children aged 11–16 years at all lumbar levels and in children aged 5–10 years at L3–L5 levels, but cannot infer the actual fixation strength of CBT screws in pediatric patients. Whether anatomical feasibility translates into sufficient biomechanical fixation requires dedicated *in vitro* and *in vivo* biomechanical investigations. Accurate screw placement is therefore a pivotal factor in safeguarding surgical safety for pediatric CBT procedures, and the biomechanical performance of short-diameter CBT screws ($\leq$5.0 mm) in the pediatric lumbar spine remains to be further verified. For future clinical application in young children with suitable anatomical conditions, intraoperative navigation or robot-assisted techniques may enhance screw placement accuracy by enabling real-time three-dimensional visualization of the pedicle and vertebral body anatomy [30].

Zindrick *et al*. [31] quantified the morphometric characteristics of the pedicles of the immature thoracolumbar spine and found pedicle width increased from 3–5 years (3.9 mm at L1 and L2, 5.1 mm at L3, 6.6 mm at L4, 8.0 mm at L5) to 18–19 years (6.6 mm at L1, 6.9 mm at L2, 8.7 mm at L3, 11.5 mm at L4, 15.6 mm at L5). Zhang *et al*. [32] characterized the growth of the vertebral column *in vivo*, showing pedicle width increased from 0–3 years (4.1 mm at L1, 4.2 mm at L2, 5.1 mm at L3, 6.1 mm at L4, 7.3 mm at L5) to 8–10 years (5.7 mm at L1, 5.8 mm at L2, 7.3 mm at L3, 9 mm at L4, 10.5 mm at L5). Senaran *et al*. [33] investigated the pediatric pedicle morphology, and their results showed that the smallest diameter was at L1 (2.3 mm for 5–8 years of age and 3 mm for 9–10 years of age), whereas L5 had the largest diameter (6.17 mm for 5–8 years of age and 8.72 mm for 9–10 years of age). According to a study by Shaikh *et al*. [34], pedicle width also increased from 5–7 years (4.87 mm at L1, 5.19 mm at L2, 6.76 mm at L3, 8.54 mm at L4, 10.63 mm at L5) to 14–16 years (7.09 mm at L1, 7.40 mm at L2, 8.88 mm at L3, 11.18 mm at L4, 14.47 mm at L5). Thus, these measurements were consistent with the maximal screw diameter obtained in our study.

Nevertheless, the results of this study should be interpreted in light of its limitations. First, anatomical measurements may vary across populations; however, all CT scans included in this analysis were obtained from Asian pediatric patients, which may limit the generalizability of the findings. Second, although all morphometric measurements were independently performed by two experienced observers and averaged for final analysis, intra- and inter-observer reliability were not formally assessed. In addition, left- and right-sided measurements were averaged for analysis, which may have limited the evaluation of potential bilateral asymmetry. Although this approach reduces inter-observer variability and random measurement error, the absence of intra-observer reliability assessment and side-specific analysis may affect the robustness of the measurements and preclude evaluation of potential bilateral asymmetry. Finally, given the complex trajectory of the CBT technique—following a caudocephalad path in the sagittal plane and a laterally directed path in the transverse plane—preoperative three-dimensional CT assessment may still be necessary, raising the exposure risk to radiation from preoperative CT scans. Accordingly, radiation-free alternatives for surgical planning have been proposed. For instance, Altorfer *et al*. [35] utilized magnetic resonance imaging (MRI) combined with robot-assisted localization technology, while Shilo *et al*. [36] employed a technique for converting MRI data into high-resolution synthetic CT (sCT) images. Future studies should further validate the accuracy of MRI-based measurements of CBT parameters in the pediatric lumbar spine, thereby providing a safer preoperative assessment option for minimally invasive spinal surgery in children.

Conclusions

The present study demonstrates the anatomical feasibility of CBT screw placement in the pediatric lumbar spine. Systematic morphometric analysis across age groups and vertebral levels—including measurements of maximum screw length, diameter, lateral angle, and cephalad angle—revealed consistent age-related trends and segmental variations. Furthermore, CBT applicability was significantly higher in patients aged 11–16 years. These findings provide detailed anatomical references to guide individualized CBT screw insertion in pediatric posterior lumbar surgery. Our research results also underscore the need to consider patient age, sex, and lumbar level when determining screw dimensions and trajectory, as these factors may influence the anatomical suitability of CBT fixation. Future studies integrating biomechanical validation and clinical follow-up are recommended to further assess the translational relevance of these morphometric data.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Author Contributions

JX, ZGZ and JC conceptualized and designed the research. JX and YC acquired the data. JX and XYW analyzed and interpreted the findings. JC and XYW wrote the article. ZGZ conducted the literature search. All authors contributed to the critical revision of the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The research protocol was reviewed and approved by the Ethics Committee of Jinhua Municipal Central Hospital (Approval Number: 2018-117). The requirement for written informed consent was waived by the Ethics Committee because of the retrospective nature of the study and the use of anonymized imaging data. The study was conducted in accordance with the ethical principles of the Declaration of Helsinki.

Acknowledgment

Not applicable.

Funding

This work is supported by a grant from the General Project of Jinhua Science and Technology Bureau (Grant No. 2019-4-004), Project of Jinhua Municipal Central Hospital (Grant No. JY2018-1-01) and Key Project of Jinhua Municipal Science and Technology Plan (Grant No. 2021-3-074).

Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.62713/aic.4529.

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