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RESEARCH

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An imaging anatomical study on percutaneous vertebral augmentation for thoracic spine via the unilateral transverse process-pedicle approach

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Abstract

Background Percutaneous vertebral augmentation (PVA) via the unilateral transverse process-pedicle approach (UTPPA) has shown promise for treating painful osteoporotic vertebral compression fractures (OVCFs). This study aimed to investigate the anatomical parameters of PVA for thoracic spine via the UTPPA using a three-dimensional computed tomography (3D CT) database.

Methods PVA was simulated through the UTPPA on 3D CT scans on 100 patients (50 men and 50 women), involving a total of 1200 thoracic vertebral bodies (T1-T12). Anatomical parameters, including the distance between the bone entry puncture point and the midline of the vertebral body (DEM), the puncture inner inclination angle (PIA), the maximum PIA (A_{max}), the middle PIA (A_{mid}), the minimum PIA (A_{min}), the safe range of the PIA (SRA), and the minimum transverse pedicle width (MTPW), were measured and compared.

Results The mean DEM ranged from 17.60 ± 2.63 mm to 22.71 ± 4.07 mm, and the A_{mid} ranged from 24.27° ± 2.21° to 40.77° ± 6.11°. The mean left DEM was significantly larger than the right ($p < 0.001$). The right SRA was significantly larger than the left ($p < 0.001$). The mean DEM, SRA and MTPW were significantly larger in men than in women ($p < 0.001$).

Conclusion In PVA for thoracic spine treatment using UTPPA, our study demonstrated that selecting this approach in men and puncturing from the right side in the thoracic vertebrae could be safer.

Keywords Percutaneous vertebral augmentation, Osteoporotic vertebral compression fracture, Thoracic spine, Unilateral transverse process-pedicle approach

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Background

Percutaneous vertebral augmentation (PVA), which includes percutaneous vertebroplasty/percutaneous kyphoplasty (PVP/PKP), has proven to be a safe and effective technique for treating painful osteoporotic vertebral compression fractures (OVCFs) [1, 2]. Recently, 3 distinct approaches of PVA have gained significant interest in this domain: the unilateral transpedicular approach (UTPA), the bilateral transpedicular approach (BTPA), and the unilateral transverse process-pedicle approach (UTPPA). The UTPA, which involves a single puncture through one pedicle, is known for its shorter operation time and less cement volume compared to the BTPA [3, 4]. However, it may result in asymmetrical cement distribution, potentially compromising vertebral stability. The BTPA, on the other hand, involves bilateral punctures and is associated with more symmetrical cement distribution, but it requires longer operation time and higher radiation exposure. The UTPPA, a modified version of the UTPA, aims to combine the benefits of both approaches by facilitating a puncture that reaches or crosses the midline of the vertebral body, thereby achieving more symmetric cement distribution while maintaining the efficiency of a unilateral procedure. Recent studies have demonstrated that the UTPPA offers comparable clinical outcomes to the BTPA, making it a promising alternative for the treatment of osteoporotic vertebral compression fractures (OVCFs) [5–7]. Compared to the BTPA, UTPPA offers equally effective results, yielding shorter operation time, lower complication rates, and reduced costs and radiation exposure [8–19]. But the complications related to the puncturing procedure through the pedicle remain a concern [20]. Improper insertion can lead to cement extravasation, which is the most frequently reported complication of PVA. The leakage rate can be up to 65% [21]. In UTPPA, the insertion can be challenging, especially in the thoracic spine with narrow and differently oriented pedicles [20, 22]. Therefore, the study of the anatomical characteristics of thoracic spine is crucial for surgeons.

Despite the growing use of PVA via UTPPA, there have been limited imaging anatomical studies on this approach in the thoracic spine. To address this gap, the study aimed to quantify three critical anatomical parameters for PVA via UTPPA in the thoracic spine: (1) the distance from the bone entry puncture point to the midline (DEM), (2) the puncture inner inclination angle (PIA), and (3) the minimum transverse pedicle width (MTPW). These parameters were analyzed across vertebral levels (T1-T12), genders, and sides to optimize preoperative planning and reduce complications.

Materials and methods

Study population

A retrospective analysis was conducted on 3D CT scans of the thoracic spine (T1-T12) from 100 consecutive patients (50 men, 50 women) at our institution between March 2023 and August 2024. All CT scans were performed as part of routine clinical evaluations prior to the study, and no additional scans were obtained solely for research purposes. The patients, aged between 20 and 72 years old (average age, 43.88 years.), presented with back pain. Inclusion criteria included: (1) non-specific back pain requiring diagnostic thoracic spine CT imaging, and (2) CT scans with a slice thickness ≤ 0.6 mm and presence of a radiopaque ruler embedded in the CT image. Patients with thoracic spine fractures, tumors, deformities and severe degeneration which might affect measurements were excluded.

This study was approved by the ethics committee of Dongzhimen Hospital Affiliated to Beijing University of Chinese Medicine (approval No. 2024DZMEC-543-02). We communicated with each participant by phone and obtained their verbal consent to participate in the study.

CT scans were performed using a 128-slice CT scanning system (SOMATOM Definition AS). Scanning parameters: Tube voltage: 120 kV; Tube current: adaptively set by CareDose machine; Scanning layer thickness: 0.6 mm; Layer spacing: 1 mm; Reconstruction layer thickness: 5 mm. Anteroposterior CT scout radiographs and T1-T12 slices passing through the widest pedicle diameter from left to right were selected. Raw data in Digital Imaging and Communications in Medicine (DICOM) format was collected.

Measurement of anatomical parameters was conducted using the software MicroDicom DICOM viewer (version 2.9.2.1566, MicroDicom Ltd, Bulgaria), with precision to 0.01 mm for lengths and 0.01° for angles.

Measurement method

The measurement methods described by Wang et al. were used (Fig. 1) [6]. The middle puncture course passed the midpoint of the narrowest pedicle and reached the anterior one-third of the midline (target point, T) through the selected slice on CT [23, 24]. The puncture inner inclination angle (PIA) was the angle measured between the midline and the puncture course. On both sides, the distance from the bone entry puncture point to the midline (DEM), the maximum PIA (A_{max}), the middle PIA (A_{mid}), the minimum PIA (A_{min}) and the minimum transverse pedicle width (MTPW) were measured. The safe range of the PIA (SRA = A_{max} - A_{min}) was calculated. The MTPW was measured as the minimum transverse pedicle width on axial CT at the level of maximum pedicle height. A MTPW ≥ 4.0 mm was considered safe for puncture, as

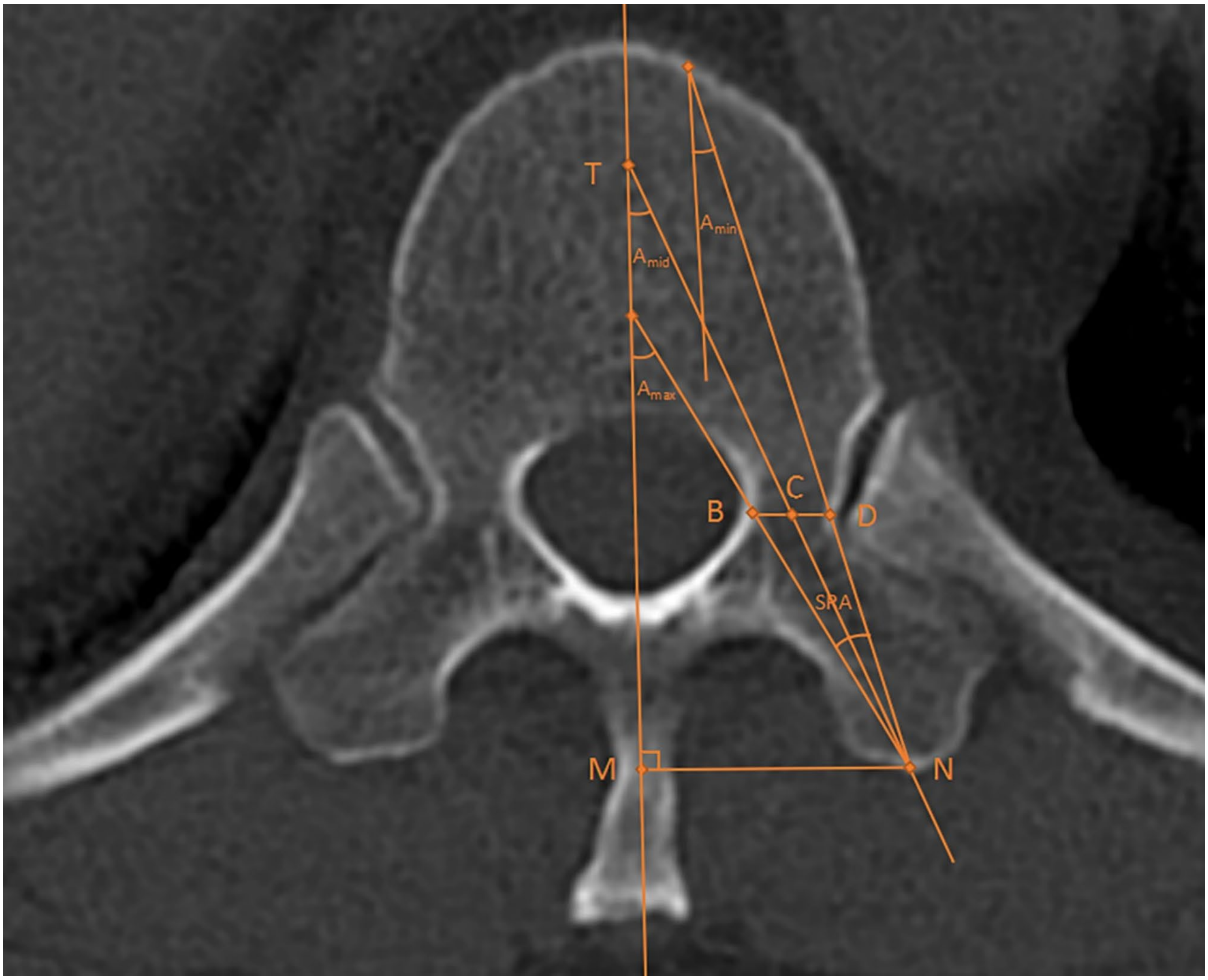

Fig. 1 Measurement of the DEM, MTPW, and angles. TM indicates the midline of the vertebral body, and the target point T is positioned at the anterior one-third of this line. N indicates the bone entry puncture point in the UTPPA, where the puncture course intersects with the transverse process through the selected slice on CT. MN indicates the distance between the bone entry puncture point and the midline (DEM). B and D indicate the inner edges of the medial and lateral cortex of the narrowest pedicle on the selected CT slice, respectively. BD indicates the minimum transverse pedicle width (MTPW). C indicates the crossing point between the puncture path and BD. When point C is between B and D, the puncture can be considered as a successful puncture. The puncture inner inclination angle (PIA) was the angle measured between the midline and the puncture course. When point C is the midpoint of BD, CN is the middle puncture path, and A_{mid} indicates the middle PIA. A_{max} indicates the maximum PIA. A_{min} indicates the minimum PIA. The safe range of the PIA (SRA = A_{max} - A_{min}) can be calculated, within which the puncture could be completed safely

the diameter of the commonly used 11-gauge needle is 3.05 mm.

The data were collected by 4 radiologists. To ensure the consistency of measurements, two spinal surgeons independently performed all anatomical measurements (DEM, PIA, MTPW) on the same set of 3D CT scans.

Statistical analysis

All data were presented as means ± standard deviations. IBM SPSS Statistics 26.0 (IBM Corporation, Armonk, NY) was used for the statistical evaluation. The interobserver reliability for measured data was assessed using the intraclass correlation coefficient (ICC). An ICC value ≥ 0.75 was considered indicative of excellent reliability. Normality was assessed using Kolmogorov-Smirnov test. Normally distributed data were analyzed using paired t-tests for side-to-side comparisons and independent t-tests for gender comparisons. For non-normally distributed data, Wilcoxon signed-rank tests were applied for side-to-side comparisons, Mann-Whitney U tests were used for gender comparisons, and Kruskal-Wallis H tests were used for comparisons among different levels. Statistical analyses were two-sided, and $p < 0.05$ was considered statistically significant.

Results

DEM

The measured data of DEM showed excellent agreement between the two independent spinal surgeons (ICC = 0.93). Significant differences in DEMs were observed between the left and right sides, as well as between genders (Table 1). The left DEM was significantly larger than the right ($p < 0.001$, Wilcoxon signed-rank test). The DEM between the left and right sides was significantly different for T6 to T11. The DEM in men was significantly larger than that in women ($p < 0.001$, Mann-Whitney U test), with significant variations observed at T2, T3, T7, T10, T11 and T12.

The DEMs were significantly different among different levels of the thoracic spine ($p < 0.001$, Kruskal-Wallis H test) (Fig. 2). The mean DEM ranged from 17.60 ± 2.63 mm (T5) to 22.71 ± 4.07 mm (T1). The mean DEM showed a stepwise decrease from T1 to T5 and increase from T5 to T12.

PIA (A_{max}, A_{mid}, A_{min}, SRA)

The measured data of PIA showed good agreement between surgeons (ICC = 0.89). The left A_{max} and A_{min} were significantly larger than the right (A_{max} $p = 0.001$, Wilcoxon signed-rank test; A_{min} $p < 0.001$, Wilcoxon signed-rank test) (Table 2). No statistical differences were found in A_{mid} between the right and left sides. The A_{min} and A_{mid} in men were significantly smaller than that in women (A_{min} $p < 0.001$, independent t-test; A_{mid} $p = 0.007$, Mann-Whitney U test). There were no statistical differences in A_{max} between men and women.

The A_{max}s, A_{mid}s and A_{min}s were significantly different among different levels ($p < 0.001$, Kruskal-Wallis H test) (Figs. 3, 4 and 5). The minimum mean A_{max} and mean A_{mid} values were recorded at T7 (30.24°±2.48° and 24.27°±2.21°, respectively), while the maximum values were at T1 (51.56°±5.83°and 40.77°±6.11°, respectively). The mean A_{max} and A_{mid} showed a stepwise decrease from T1 to T7 and increase from T7 to T12. The mean A_{min} was the smallest at T8 (17.25°±3.93°) and the largest at T1 (28.50°±6.74°) (Fig. 5).

The right SRA was significantly larger than the left ($p < 0.001$, Wilcoxon signed-rank test), particularly in T2 and T5-T10 (Table 3). The SRA in men was significantly larger than that in women ($p < 0.001$, Mann-Whitney U test), particularly in T1-T6.

The SRAs also exhibited significant differences across various levels ($p < 0.001$, Kruskal-Wallis H test), with the smallest mean SRA observed at T4 (12.27°±3.94°) and the largest at T1 (23.39°±7.55°) (Fig. 6). These values followed a stepwise pattern, showing a decrease from T1 to T4 and an increase from T4 to T12.

MTPW

The measured data of MTPW showed excellent agreement between surgeons (ICC = 0.91). There were no significant differences in the MTPW between right and left ($p = 0.300$, Wilcoxon signed-rank test) (Table 4). The MTPW in men was significantly larger than that in women ($p < 0.001$, independent t-test), and the difference was significant at every level of thoracic spine.

As depicted in Fig. 7, the MTPWs among different levels were significantly different ($p < 0.001$, Kruskal-Wallis H test). The mean MTPW was smallest at T4 (3.59 ± 1.06 mm) and biggest at T11 (6.67 ± 1.77 mm). The mean MTPW decreased from T1 to T4 and increased

Table 1 DEMs between the left and right sides, and between men and women. (mm)

Level	Side		p	Gender		p
	Left	Right		Men	Women	
T1	22.64 ± 3.83	22.78 ± 4.32	0.634	23.23 ± 4.43	22.2 ± 3.64	0.093#
T2	20.20 ± 3.13	19.71 ± 2.90	0.136#	20.22 ± 2.70	19.69 ± 3.31	0.030*#
T3	18.57 ± 2.80	18.23 ± 2.31	0.601#	18.84 ± 2.50	17.96 ± 2.56	0.006*#
T4	17.66 ± 2.34	17.69 ± 2.39	0.856#	17.93 ± 2.22	17.41 ± 2.47	0.120
T5	17.83 ± 2.79	17.37 ± 2.46	0.258#	17.72 ± 2.51	17.48 ± 2.75	0.366#
T6	18.63 ± 2.89	17.34 ± 3.27	< 0.001*	18.36 ± 3.18	17.61 ± 3.08	0.142#
T7	19.35 ± 2.74	17.58 ± 3.12	< 0.001*	18.90 ± 2.95	18.04 ± 3.12	0.047*
T8	19.79 ± 3.03	18.23 ± 3.20	< 0.001*#	19.32 ± 3.24	18.70 ± 3.16	0.170
T9	20.55 ± 3.43	19.13 ± 3.98	< 0.001*	20.29 ± 4.24	19.40 ± 3.20	0.095
T10	22.05 ± 2.89	20.78 ± 3.43	< 0.001*	21.89 ± 3.18	20.94 ± 3.21	0.044*#
T11	22.60 ± 2.92	21.69 ± 2.96	0.005*	22.54 ± 3.48	21.74 ± 2.30	0.003*#
T12	22.30 ± 2.38	22.44 ± 2.45	0.460	22.93 ± 2.36	21.81 ± 2.34	< 0.001*
Mean	**20.18 ± 3.44**	**19.42 ± 3.67**	**< 0.001*#**	**20.18 ± 3.68**	**19.41 ± 3.42**	**< 0.001*#**

Abbreviations: DEM, distance from the bone entry puncture point to the midline.

Data are expressed as mean ± standard deviation.

* indicates significant differences between left and right or men and women ($p < 0.05$).

# indicates measured data with non-normality.

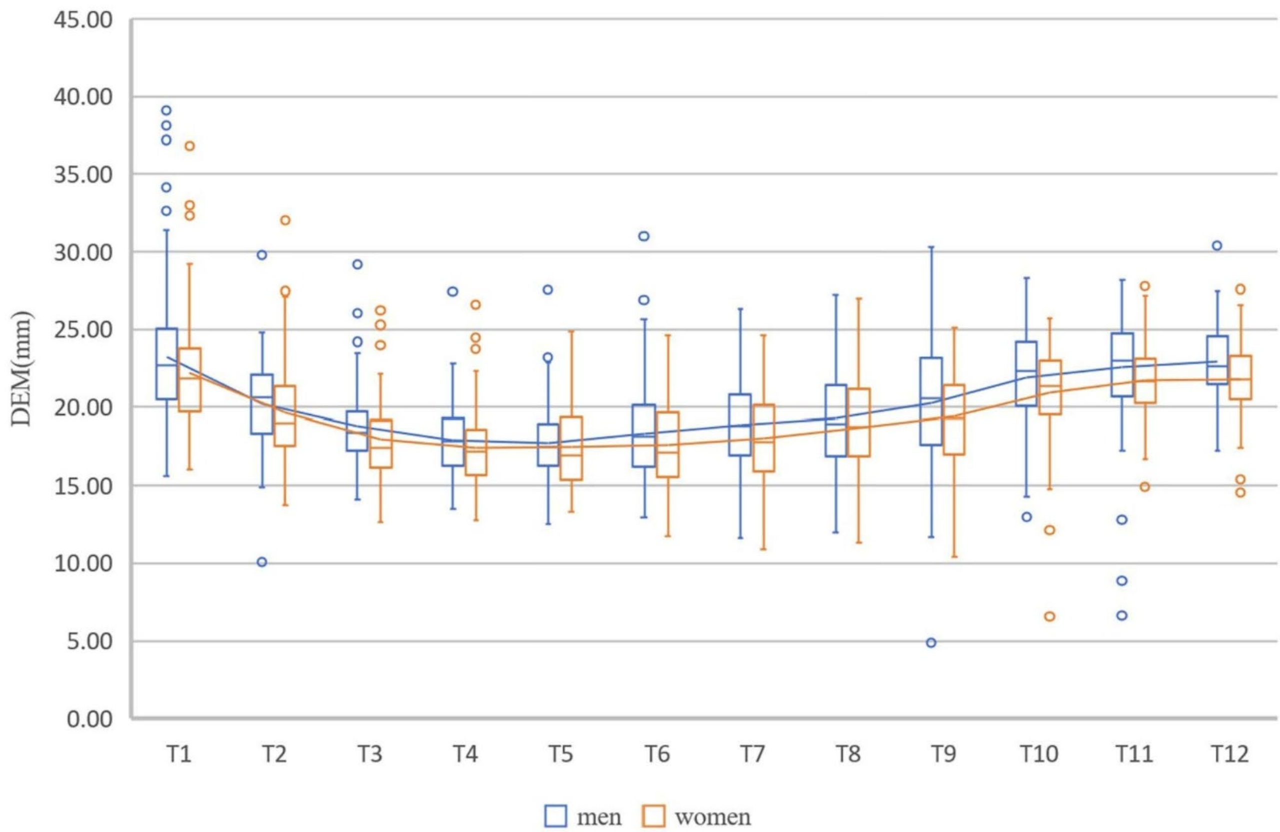

Fig. 2 The DEMs of thoracic spines (mm). DEM indicates distance from the bone entry puncture point to the midline. The mean DEM ranged from 17.60 ± 2.63 mm (T5) to 22.71 ± 4.07 mm (T1)

from T4 to T11 in a stepwise fashion. The mean MTPW values for T3-T5 were less than 4 mm.

Discussion

OVCF remain a significant challenge in elderly populations [25–28], with PVA offering effective pain relief and vertebral stabilization [15–17]. While the UTPA reduces operative time and radiation exposure compared with the BTPA [8–19], its asymmetrical cement distribution may compromise vertebral stability. The UTPPA is a modified version of the UTPA and addresses these limitations by enabling midline cement distribution through a single puncture [5, 11, 29].

Puncturing the thoracic spine via UTPPA presents challenges due to not only the difficult visualization of anatomical landmarks but also narrow and variably oriented pedicles, especially in the upper and middle thoracic spine [20, 22]. A successful puncture can ensure symmetrical bone cement distribution and prevent complications [30]. It is essential to achieve a puncture that reaches or crosses the midline of the vertebral body, with the optimal puncture point located in the anterior one-third region from the median vertebral body [14, 23, 31]. To achieve this, surgeons must localize the entry point outside of the pedicle projection and close to the vertebral body, with a larger PIA compared to BTPA [6]. A small PIA may lead to uneven distribution of bone cement, potentially reinforcing only one side of the vertebra [15]. Conversely, an excessively large PIA can damage the medial pedicle wall, resulting in bone cement leakage and neurovascular injuries [15]. Detailed 3D CT measurements and thorough preoperative planning are critical [23]. In our study, we conducted anatomical measurements to offer pertinent morphological data to surgeons, enhancing the surgical safety. The observed gender and side differences in DEM, PIA, and MTPW highlight the need for individualized surgical strategies.

In the study, males are likely attributed to having significantly larger DEM, the same as SRA and MTPW, due to the gender-specific differences in skeletal size and pedicle morphology. The larger DEM on the left side compared to the right, especially for T6 to T11, may be attributed to asymmetrical biomechanical loading patterns in the thoracic spine, potentially influenced by handedness or habitual postures. The predominantly right-handed population prefers loading the right side, and repetitive rotational or lateral bending movements might lead

Table 2 PIAs between the left and right sides, and between men and women (°)

Level	PIA	Side		p	Gender		p
		Left	Right		Men	Women	
T1	A_{max}	52.26 ± 8.45	51.19 ± 8.48	0.011*#	52.89 ± 8.80	50.56 ± 7.99	0.048*#
	A_{mid}	40.57 ± 6.20	40.98 ± 6.07	0.185	40.98 ± 6.39	40.56 ± 5.87	0.569#
	A_{min}	28.85 ± 6.10	27.82 ± 6.15	0.121#	27.72 ± 6.19	28.95 ± 6.04	0.155
T2	A_{max}	41.65 ± 5.57	41.58 ± 6.28	0.656#	42.60 ± 5.62	40.63 ± 6.08	0.003*#
	A_{mid}	33.08 ± 4.47	33.61 ± 4.76	0.066	33.44 ± 4.36	33.26 ± 4.88	0.552#
	A_{min}	24.98 ± 5.14	23.78 ± 4.35	0.009*#	24.01 ± 4.37	24.75 ± 5.16	0.271
T3	A_{max}	35.32 ± 4.01	34.81 ± 3.96	0.070	35.98 ± 4.09	34.15 ± 3.67	0.001*#
	A_{mid}	28.33 ± 3.12	28.82 ± 3.05	0.039*	28.79 ± 3.07	28.35 ± 3.10	0.316
	A_{min}	21.98 ± 3.71	21.09 ± 3.72	0.009*	21.05 ± 3.28	21.99 ± 4.09	0.074
T4	A_{max}	32.51 ± 2.70	32.17 ± 3.42	0.202	32.95 ± 3.25	31.74 ± 2.77	0.008*#
	A_{mid}	26.15 ± 2.35	26.65 ± 2.67	0.082#	26.40 ± 2.60	26.40 ± 2.46	0.641#
	A_{min}	20.35 ± 3.42	19.79 ± 3.82	0.106	19.41 ± 3.46	20.41 ± 3.69	0.010*
T5	A_{max}	31.12 ± 2.51	31.04 ± 2.78	0.788	31.64 ± 3.08	30.51 ± 1.96	0.002*
	A_{mid}	24.98 ± 2.19	25.38 ± 2.35	0.102	25.06 ± 2.50	25.29 ± 2.03	0.484
	A_{min}	19.32 ± 3.76	18.24 ± 3.79	0.004*#	17.96 ± 3.85	19.60 ± 3.59	0.002*
T6	A_{max}	30.93 ± 2.56	30.66 ± 2.98	0.395	31.17 ± 3.03	30.41 ± 2.45	0.081#
	A_{mid}	24.58 ± 2.01	24.56 ± 2.90	0.954	24.55 ± 2.82	24.58 ± 2.12	0.939
	A_{min}	19.11 ± 3.51	17.03 ± 4.43	< 0.001*	17.71 ± 4.20	18.42 ± 4.04	0.232
T7	A_{max}	30.18 ± 2.37	30.29 ± 2.61	0.731	30.18 ± 2.60	30.29 ± 2.38	0.741
	A_{mid}	24.47 ± 2.15	24.07 ± 2.26	0.127	24.06 ± 2.35	24.48 ± 2.06	0.188
	A_{min}	18.62 ± 3.05	16.15 ± 3.98	< 0.001*	17.00 ± 3.29	17.78 ± 4.14	0.146
T8	A_{max}	30.63 ± 2.76	31.05 ± 2.72	0.149	30.60 ± 2.89	31.08 ± 2.58	0.308#
	A_{mid}	24.51 ± 2.19	24.42 ± 2.33	0.727	24.10 ± 2.36	24.83 ± 2.09	0.005*#
	A_{min}	18.24 ± 3.35	16.25 ± 4.25	< 0.001*	16.73 ± 3.73	17.77 ± 4.10	0.007*#
T9	A_{max}	31.47 ± 3.90	31.51 ± 2.73	0.931	31.18 ± 3.13	31.80 ± 3.55	0.187#
	A_{mid}	25.07 ± 2.69	24.81 ± 2.40	0.232	24.61 ± 2.69	25.27 ± 2.36	0.068
	A_{min}	18.61 ± 3.34	16.53 ± 4.52	< 0.001*#	17.26 ± 4.10	17.88 ± 4.10	0.182#
T10	A_{max}	33.56 ± 3.27	33.11 ± 3.28	0.151	32.98 ± 3.31	33.69 ± 3.21	0.123
	A_{mid}	26.29 ± 2.63	26.09 ± 2.65	0.414	25.71 ± 2.64	26.67 ± 2.55	0.009*
	A_{min}	18.85 ± 3.59	16.92 ± 4.39	< 0.001*	17.19 ± 4.11	18.58 ± 4.02	0.015*#
T11	A_{max}	37.82 ± 5.75	35.86 ± 4.32	< 0.001*#	36.45 ± 5.04	37.23 ± 5.28	0.174#
	A_{mid}	28.25 ± 4.14	27.92 ± 2.93	0.044*#	27.83 ± 3.13	28.34 ± 3.97	0.046*#
	A_{min}	18.49 ± 3.74	16.45 ± 4.28	< 0.001*#	17.05 ± 4.29	17.89 ± 3.96	0.289#
T12	A_{max}	39.29 ± 5.29	39.08 ± 5.14	0.713#	38.35 ± 5.08	40.03 ± 5.22	0.008*#
	A_{mid}	29.55 ± 2.78	30.18 ± 2.91	0.022*#	29.34 ± 3.12	30.39 ± 2.47	0.009*
	A_{min}	18.08 ± 5.04	17.85 ± 4.84	0.511#	18.00 ± 3.95	17.93 ± 5.77	0.365#
Mean	$\mathbf{A_{max}}$	**35.56 ± 7.62**	**35.20 ± 7.36**	**< 0.001*#**	**35.51 ± 7.72**	**35.14 ± 7.25**	**0.199#**
	$\mathbf{A_{mid}}$	**27.98 ± 5.60**	**28.12 ± 5.75**	**0.176#**	**27.91 ± 5.81**	**28.20 ± 5.54**	**0.007*#**
	$\mathbf{A_{min}}$	**20.46 ± 5.15**	**18.99 ± 5.60**	**< 0.001*#**	**19.25 ± 5.25**	**20.18 ± 5.56**	**< 0.001***

Abbreviations: PIA, puncture inclination angle; A_{max}, the maximum PIA; A_{mid}, the middle PIA; A_{min}, the minimum PIA.

Data was expressed by mean ± standard deviation.

* indicates significant differences between left and right or men and women ($p < 0.05$).

# indicates measured data with non-normality.

to adaptive hypertrophy of the contralateral pedicle and transverse process, especially for T6 to T11, which are prone to be affected by the loading. Interestingly, a prior study concentrating on a similar procedure in the lumbar spine showed that the DEM of UTPPA was significantly larger on the right than the left [7]. Given the symmetry of human vertebrae, variations between left and right might be affected by patient positioning during CT scans. Further research is necessary to validate these observations. In addition, the larger SRA on the right side compared to the left supports the preference for right-sided punctures in the thoracic spine. The wider SRA provides a greater margin of error for needle placement. Moreover, the smaller MTPW in women, particularly at T3-T5, suggests that female patients may be at higher risk of pedicle wall breach during puncture, necessitating cautious

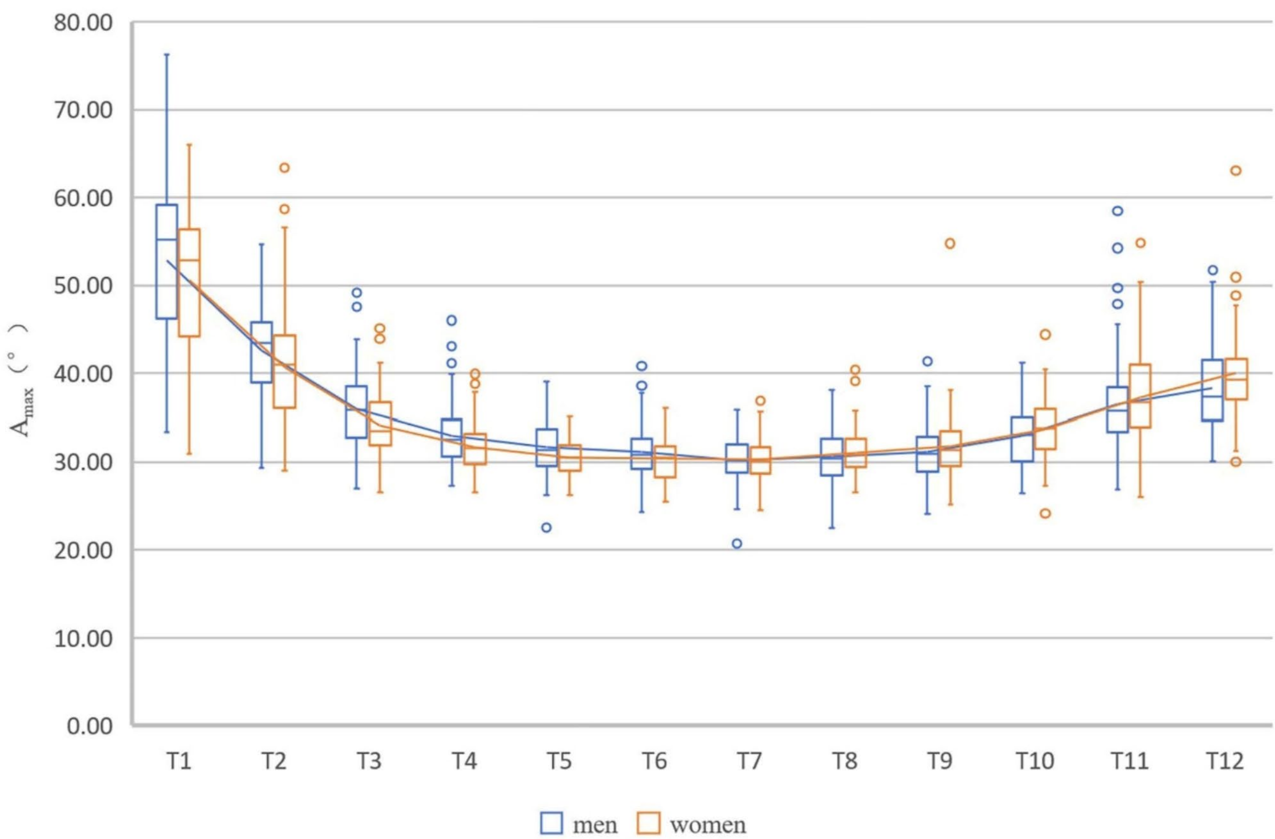

Fig. 3 The A_{max} of thoracic spines (°). A_{max} indicates the maximum PIA. The mean A_{max} ranged from 30.24°±2.48° (T7) to 51.56°±5.83° (T1)

needle selection in these levels. This finding is particularly relevant for preoperative planning, as it underscores the importance of gender-specific and side-specific considerations when determining the puncture trajectory.

Several modifications have been proposed to achieve safe puncture in the middle and upper thoracic spine with narrow pedicles [22, 32–34]. One alternative is to choose another approach. For example, it was suggested that extrapedicle puncture was more suitable in the vertebral body above T9, where the MTPW is narrow [33]. However, this method posed an increased risk of arterial injury and pneumothorax, and the procedure was more challenging due to the costovertebral joint [33]. Another option is to use a slender puncture needle for secure insertion. According to David et al., an 11-gauge needle (3.05 mm) suffices for the majority of punctures in the middle and upper thoracic spine, while a thinner puncture needle, such as 13-gauge (2.41 mm), might elevate the risk of puncture complications due to unclear radiofluoroscopic needle images and other factors [32]. Based on our research, the UTPPA is a promising option to address the challenges of puncturing safely in the middle and upper thoracic spine, given the minimum MTPW was 3.59 mm.

The findings of this study have important clinical implications for the safe and effective application of UTPPA in the thoracic spine. The anatomical measurements provided can guide surgeons in selecting the appropriate puncture side, adjusting the needle trajectory, and choosing the optimal puncture needle size. Preoperative 3D CT imaging and thorough planning are essential to minimize complications and achieve successful outcomes.

While some of the observed differences (e.g., DEM < 1 mm) are numerically small, their clinical relevance is amplified in the context of thoracic spine anatomy and surgical precision. In the thoracic spine, where the MTPW is narrow, a 1-mm deviation in the puncture trajectory could increase the risk of lateral pedicle wall breach, potentially leading to cement leakage or spinal canal intrusion. Furthermore, the potential measurement error of CT-based anatomical parameters must also be considered. High-resolution CT scans (0.6-mm slice thickness) combined with dedicated DICOM software (MicroDicom, precision: 0.01 mm) can provide submillimetric accuracy. Additionally, a high-quality systematic review has found that there is no statistical difference in measuring the pedicle via radiography (CT) or directly [35].

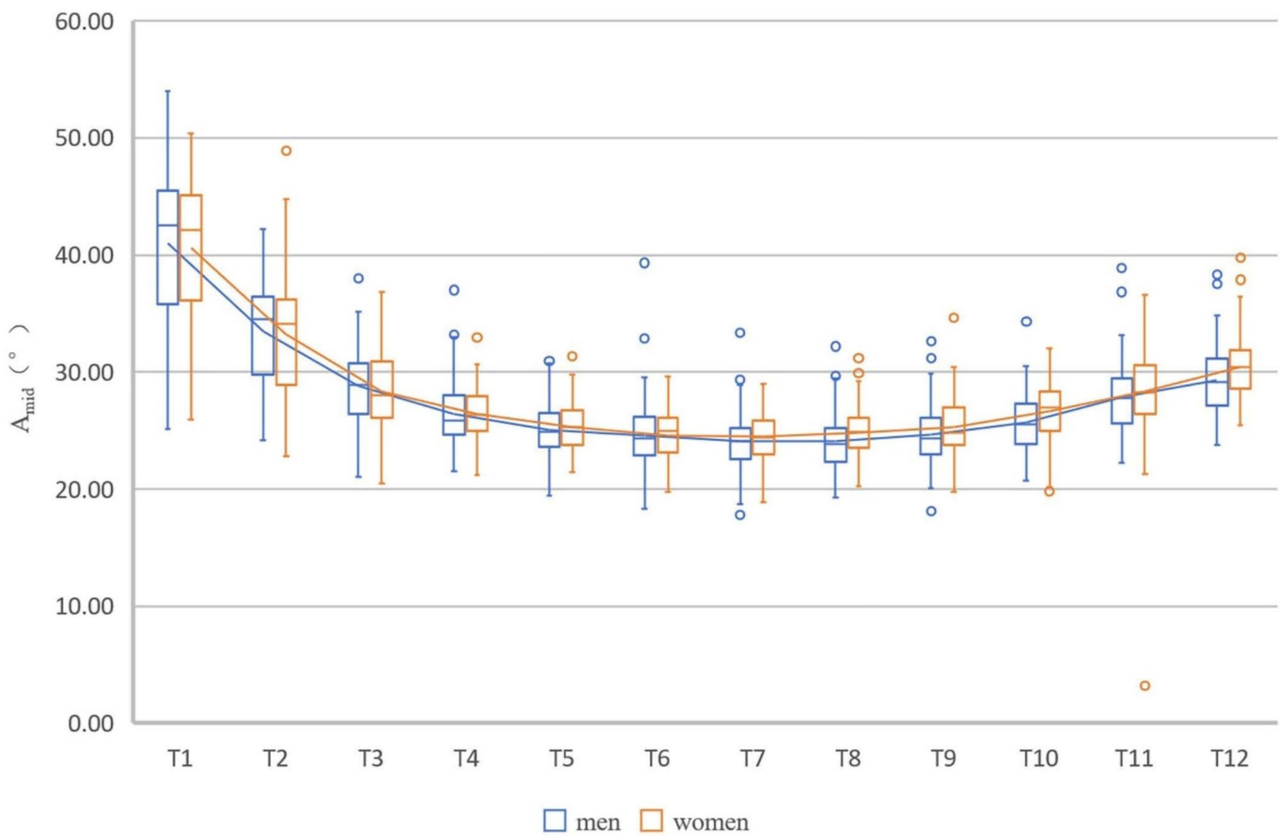

Fig. 4 The A_{mid} of thoracic spines (°). A_{mid} indicates the middle PIA. The mean A_{mid} ranged from 24.27°±2.21° (T7) to 40.77°±6.11° (T1)

As far as we know, our study provided anatomical imaging measurements of PVA via UTPPA for the thoracic spine for the first time, which is essential to enhance the surgical safety. But there are several limitations that should be acknowledged. Firstly, despite using the mean value of measurements from two spinal surgeons to minimize errors and the high ICC values for all parameters indicating robust interobserver reliability, the measurement error is inevitable. Secondly, the sample size was relatively small, and the patients were limited to Chinese population. Previous studies have reported racial differences in pedicle morphology among populations [35, 36]. Therefore, the applicability of our results to non-Chinese populations may require further validation. Future multicenter studies should aim to replicate these findings in diverse populations to establish the universality of the anatomical parameters identified in this study. Thirdly, the relatively young patients selected in the study and the exclusion of patients with fractures in our study, despite focusing on OVCFs, could be considered a limitation. While OVCFs predominantly affect elderly individuals, studying a younger population allows for the assessment of normal anatomical variations without the confounding effects of osteoporosis-related vertebral deformities or advanced degenerative changes. Additionally, although the study focuses on OVCFs, the exclusion of fracture cases was necessary to establish a baseline understanding of the anatomical parameters in normal thoracic vertebrae, which can later be applied to fracture cases in clinical practice. The addition of an observation group with patients having thoracic spine fractures could have strengthened the study's persuasiveness. However, finding enough patients with fractures for each specific level of the thoracic spine with homogeneous baseline characteristics proved challenging. Furthermore, previous imaging anatomical studies on PVA also excluded patients with fractures due to the potential impact on measurement accuracy [6, 7, 37]. Future studies focusing specifically on elderly osteoporotic patients are warranted to validate these findings and assess their applicability in this population. Comparing clinical outcomes of UTPPA versus conventional transpedicular approaches, and developing AI-based tools for automated measurement of DEM, PIA, and MTPW to enhance surgical precision also worth exploring in research.

Conclusion

This study provides critical anatomical insights for optimizing PVA via UTPPA in the thoracic spine. Gender and side significantly influenced key parameters: men

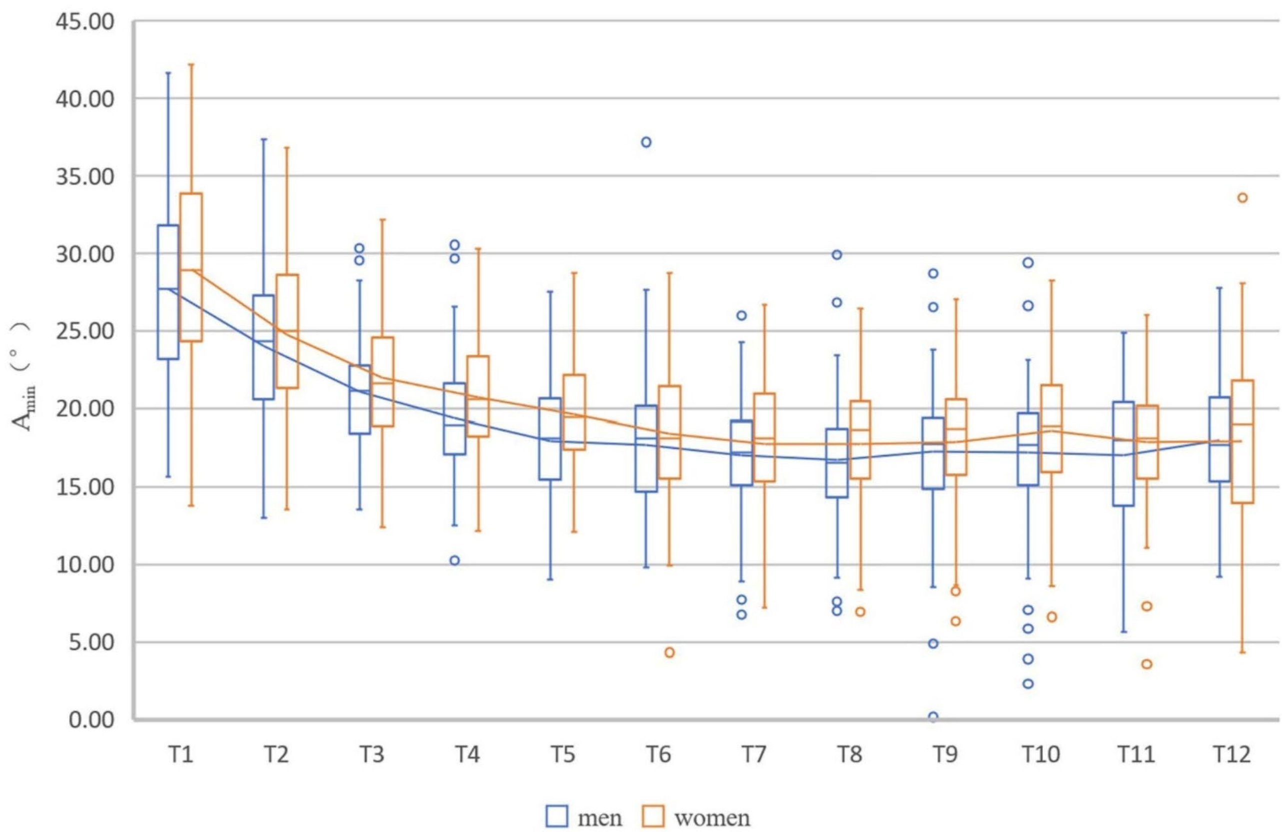

Fig. 5 The A_{min} of thoracic spines (°). A_{min} indicates the minimum PIA. The mean A_{min} ranged from 17.25°±3.93° (T8) to 28.50°±6.74° (T1)

Table 3 SRAs between the left and right sides, and between men and women (°)

Level	Side		*p*	Gender		*p*
	Left	Right		Men	Women	
T1	23.41 ± 7.31	23.37 ± 7.85	0.952	25.17 ± 7.66	21.61 ± 7.07	0.001*#
T2	16.67 ± 5.29	17.80 ± 5.40	0.008*	18.59 ± 5.05	15.88 ± 5.34	< 0.001*
T3	13.34 ± 4.24	13.73 ± 4.58	0.228	14.93 ± 4.22	12.16 ± 4.16	< 0.001*
T4	12.16 ± 3.60	12.37 ± 4.29	0.537	13.53 ± 3.77	11.00 ± 3.73	< 0.001*#
T5	11.80 ± 4.18	12.80 ± 4.37	0.011*#	13.69 ± 4.48	10.90 ± 3.62	< 0.001*
T6	11.82 ± 4.08	13.63 ± 4.48	< 0.001*	13.45 ± 4.23	12.00 ± 4.41	0.018*
T7	11.56 ± 3.55	14.14 ± 4.50	< 0.001*#	13.18 ± 3.64	12.52 ± 4.76	0.116#
T8	12.39 ± 4.27	14.80 ± 4.87	< 0.001*	13.87 ± 4.32	13.31 ± 5.10	0.128#
T9	12.86 ± 4.55	14.98 ± 5.05	< 0.001*#	13.92 ± 4.11	13.92 ± 5.61	0.454#
T10	14.71 ± 4.52	16.19 ± 5.11	< 0.001*	15.78 ± 4.82	15.11 ± 4.92	0.308#
T11	19.33 ± 6.66	19.41 ± 6.20	0.329#	19.40 ± 6.50	19.35 ± 6.37	0.996#
T12	21.21 ± 8.19	21.23 ± 7.43	0.640#	20.35 ± 6.24	22.10 ± 9.05	0.382#
Mean	**15.11 ± 6.53**	**16.20 ± 6.40**	**< 0.001*#**	**16.32 ± 6.20**	**14.99 ± 6.71**	**< 0.001*#**

Abbreviations: SRA, safe range of the puncture inner inclination angle.

Data was expressed by mean ± standard deviation.

* indicates significant differences between left and right or men and women ($p < 0.05$).

\# indicates measured data with non-normality.

exhibited larger DEM and wider SRA, while the right side offered a broader SRA than the left. Women demonstrated narrower MTPW, particularly at T3–T5.

Based on our findings, we recommend the following clinical practices to optimize the safety and efficacy of PVA via UTPPA in the thoracic spine: (1) Surgeons should adjust the bone entry point further laterally in male patients compared to females. (2) Puncturing from the right side in the thoracic spine is safer. (3) Female patients may require thinner puncture needles (e.g.,

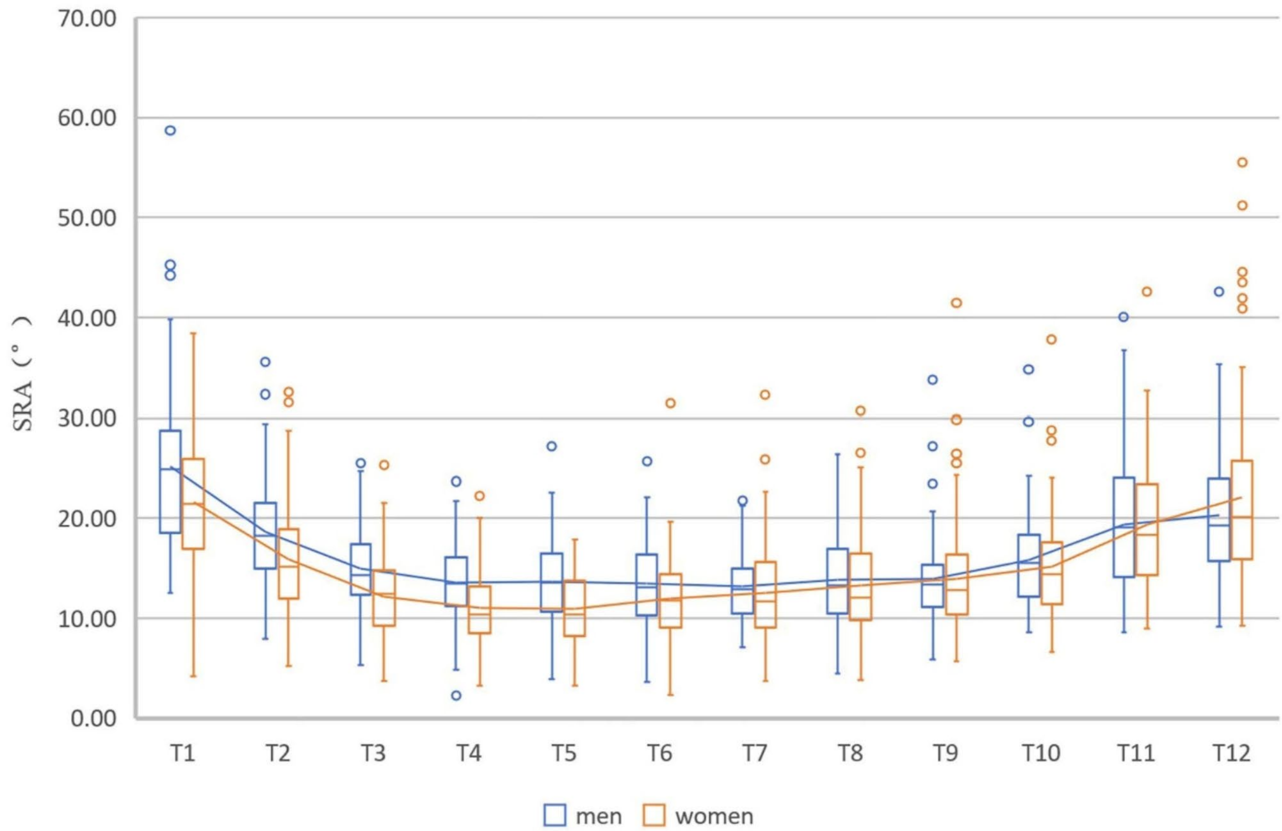

Fig. 6 The SRA of thoracic spines (°). SRA indicates safe range of the puncture inner inclination angle. The mean SRA ranged from 12.27°±3.94° (T4) to 23.39°±7.55° (T1)

Table 4 MTPWs between the left and right sides, and between men and women (mm)

Level	Side		*p*	Gender		*p*
	Left	Right		Men	Women	
T1	6.23 ± 1.67	6.21 ± 1.67	0.841	6.73 ± 1.55	5.71 ± 1.63	< 0.001*
T2	4.88 ± 1.35	4.91 ± 1.51	0.684	5.31 ± 1.36	4.48 ± 1.38	< 0.001*#
T3	3.97 ± 1.15	3.85 ± 1.18	0.095	4.33 ± 1.09	3.48 ± 1.08	< 0.001*
T4	3.61 ± 1.04	3.57 ± 1.08	0.546	4.00 ± 0.96	3.18 ± 1.00	< 0.001*#
T5	3.70 ± 1.08	3.68 ± 1.16	0.704	4.10 ± 1.06	3.28 ± 1.02	< 0.001*
T6	4.10 ± 1.15	3.99 ± 1.05	0.185	4.41 ± 1.01	3.68 ± 1.07	< 0.001*
T7	4.29 ± 1.07	4.31 ± 1.08	0.269#	4.64 ± 0.98	3.96 ± 1.06	< 0.001*#
T8	4.63 ± 1.24	4.63 ± 1.17	0.943	4.94 ± 1.22	4.33 ± 1.11	< 0.001*#
T9	5.04 ± 1.29	5.05 ± 1.35	0.859	5.43 ± 1.23	4.65 ± 1.29	< 0.001*
T10	5.92 ± 1.69	5.92 ± 1.79	0.994	6.26 ± 1.62	5.58 ± 1.79	0.005*#
T11	6.74 ± 1.83	6.60 ± 1.73	0.217	7.12 ± 1.77	6.22 ± 1.67	< 0.001*
T12	6.25 ± 1.95	6.23 ± 1.83	0.870	6.54 ± 1.78	5.95 ± 1.95	0.005*#
Mean	**4.95 ± 1.75**	**4.91 ± 1.75**	**0.300#**	**5.32 ± 1.69**	**4.54 ± 1.72**	**< 0.001***

Abbreviations: MTPW, the minimum transverse pedicle width.

Data was expressed by mean ± standard deviation.

* indicates significant differences between left and right or men and women ($p < 0.05$).

# indicates measured data with non-normality.

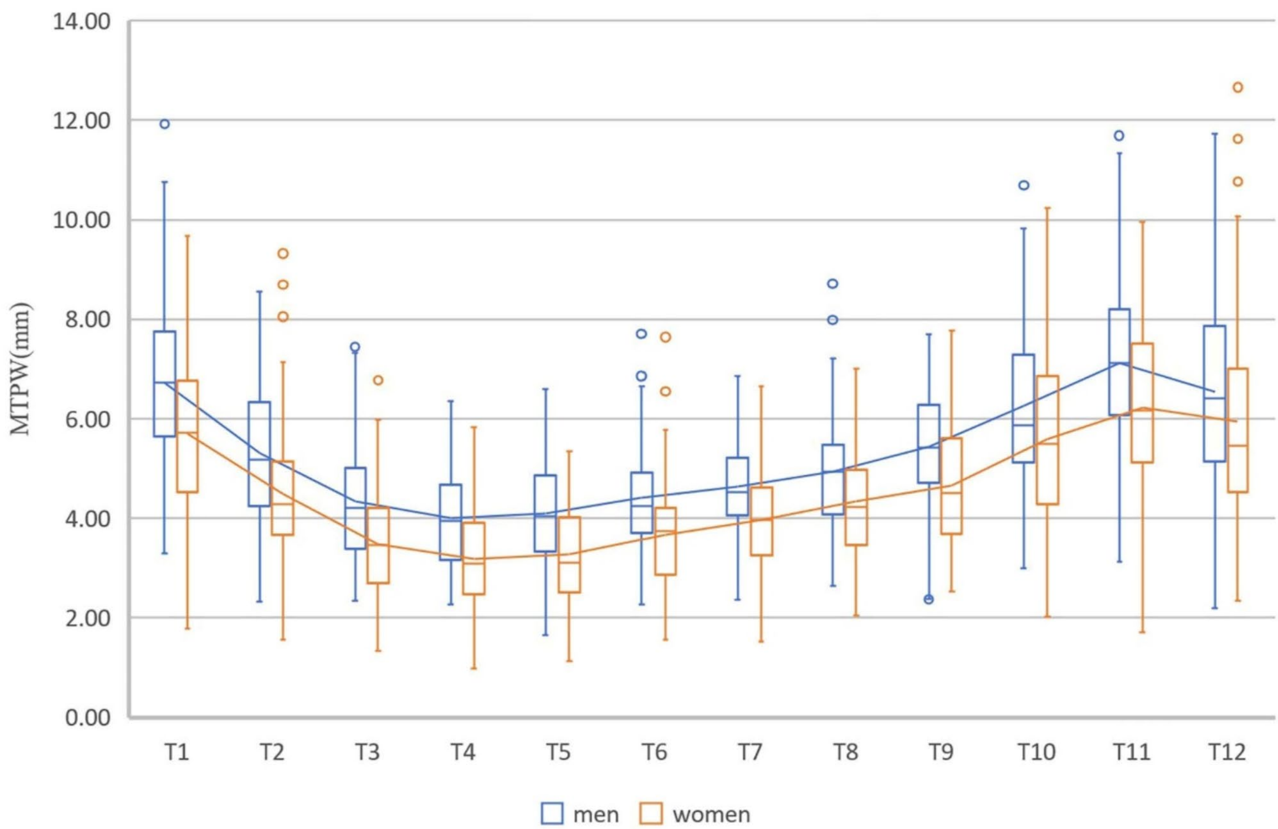

Fig. 7 The MTPW of thoracic spines (mm). MTPW indicates the minimum transverse pedicle width. The mean MTPW ranged from 3.59 ± 1.06 mm (T4) to 6.67 ± 1.77 mm (T11)

13-gauge) to safely navigate the narrow pedicles in the middle-upper thoracic spine. These strategies, supported by preoperative 3D CT planning, may reduce complications like cement leakage or spinal canal intrusion. Future studies should validate these findings in elderly and diverse populations.

Abbreviations

PVA	Percutaneous vertebral augmentation
UTPA	The unilateral transpedicular approach
BTPA	The bilateral transpedicular approach
UTPPA	Unilateral transverse process-pedicle approach
3D CT	Three-dimensional computed tomography
DEM	Distance between the bone entry puncture point and the midline of the vertebral body
PIA	Puncture inner inclination angle
A_{max}	The maximum PIA
A_{mid}	The middle PIA
A_{min}	The minimum PIA
SRA	Safe range of the PIA
MTPW	The minimum transverse pedicle width
PVP	Percutaneous vertebroplasty
PKP	Percutaneous kyphoplasty
OVCFs	Osteoporotic vertebral compression fractures
DICOM	Digital imaging and communications in medicine

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Author contributions
Conceptualization of the research and Methodology is by Shi Yin and Zhiwei Jia. Data collection is by Junxin Zou, Linfeng Zhou, Meilin Zhang and Zezhong Zeng. Formal statistical analysis is by Yan Zhang and Ying Du. Manuscript writing is by Shi Yin, Yan Zhang and Ying Du. Review and editing is by Zhiwei Jia, Zhendong Xu and Fangjun Zeng.

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Data availability
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Prior to study start, the study protocol and/or other appropriate documents were submitted to the ethics committee of Dongzhimen Hospital Affiliated to Beijing University of Chinese Medicine for approval (No. 2024DZMEC-543-02). We communicated with each participant by phone and obtained their verbal consent to participate in the study.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests.

Declaration of Conflicting Interests
Each author certifies that he or she, or a member of his or her immediate family, has no commercial association (i.e., consultancies, stock ownership,

equity interest, patent/licensing arrangements, etc.) that might pose a conflict of interest in connection with the submitted manuscript.

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