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Anatomical study of the ideal cortical bone trajectory in the lumbar spine

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Abstract

Background: To explore the ideal trajectory of lumbar cortical bone trajectory screws and provide the optimal placement scheme in clinical applications.

Methods: Lumbar computed tomography (CT) data of 40 patients in our hospital were selected, and the cortical vertebral bone contour model was reconstructed in three dimensions (3D). Depending on the different regions of the screw through the entrance and exit of the pedicle, 9 trajectories were obtained through combinational design: T-Aa, T-Ab, T-Ac, T-Ba, T-Bb, T-Bc, T-Ca, T-Cb, and T-Cc. Cortical bone trajectory (CBT) screws with appropriate diameters were selected to simulate screw placement and measure the parameters corresponding to each trajectory (screw path diameter, screw trajectory length, cephalad angle, and lateral angle), and then determine the optimal screw according to the screw parameters and screw safety. Then, 23 patients in our hospital were selected, and the navigation template was designed based on the ideal trajectory before operation, CBT screws were placed during the operation to further verify the safety and feasibility of the ideal trajectory.

Results: T-Bc and T-Bb are the ideal screw trajectories for L1–L2 and L3–L5, respectively. The screw placement point is located at the intersection of the inner 1/3 vertical line of the superior facet joint and the bottom 1/3 horizontal line of the outer crest of the vertebral lamina (i.e., 2–4 mm inward at the bottom 1/3 of the outer crest of the vertebral lamina). CBT screws were successfully placed based on the ideal screw trajectory in clinical practice. During the operation or the follow-up period, there were no adverse events.

Conclusion: CBT screw placement based on the ideal screw trajectory is a safe and reliable method for achieving effective fixation and satisfactory postoperative effects.

Abbreviations: 3D = three dimensions, CT = computed tomography, CBT = cortical bone trajectory, DICOM = Digital Imaging and Communications in Medicine, TRW = trajectory reference width, TRH = trajectory reference height.

Keywords: CBT screw, digital technology, ideal trajectory, lumbar vertebra

1. Introduction

The shortcomings of internal pedicle screw fixation have emerged gradually along with its extensive application. Because fixation through the holding force of the pedicle screw is mainly achieved through the partial contact between the screw and cancellous bone within the vertebral body, in patients with osteopenia and senile osteoporosis, in whom the bone mineral density of the vertebral bodies is reduced, the degeneration of the bone tissue

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All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

All patients were informed and signed a surgical consent before surgery.

The authors have no conflicts of interest to disclose.

The datasets generated during and/or analyzed during the current study are not publicly available, but are available from the corresponding author on reasonable request.

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structures will result in an obvious reduction in the fixation strength of the vertebral pedicle screw, as well as many postoperative complications, such as screw loosening, cut-out, and pullout, or even failure of the operation.[1–4] Although some surgeons have improved the holding force of the screw through altered screw designs or strengthening with bone cement, there are still some limitations in clinical practice.[5,6] In 2009, Santoni et al[7] increased the contact area between the screw and vertebral cortical bone by changing the screw trajectory to improve the holding force of the pedicle screw and then proposed cortical bone trajectory (CBT) screw technology. These screws can provide effective fixation in patients with osteoporosis and are less affected by cancellous bone. There are no uniform standards for placing a CBT screw. Different screw trajectories have different cortical bone contact areas, resulting in different fixation strengths. Since the diameter of the CBT screw is shorter than that of the pedicle screw, the quality of the CBT screw trajectory is particularly important. Therefore, based on the characteristics of CBT screw placement, this research designed possible trajectories using digital technology to determine the ideal trajectory for CBT screws in lumbar vertebrae through a comprehensive analysis of the safety and feasibility of screw placement and the relationships among the placement rate, cortical bone contact volume, entry point location, and screw placement angle for different trajectories with clinical operability. We then performed screw placement verification based on the ideal trajectories, thus providing a reference for the clinical application of CBT screws.

2. Data and methods

2.1. General data

In this study, the lumbar computed tomography (CT) data of 40 patients hospitalized in our hospital from October 2015 to October 2017 were used. There were 18 males and 22 females, with a mean age of 57.9 ± 17.4 years (range, 19–76 years). Inclusion criteria:

(1) adult patients, age ≥ 18 years;
(2) complete CT data of lumbar spine;
(3) complete structure of lumbar spine.

Exclusion criteria:

(1) vertebral dysplasia or lumbar deformity;
(2) fracture, infection, or tumor damage to the vertebral structure;
(3) previous lumbar surgery history.

2.2. Design principle of ideal trajectory

2.2.1. Safety and feasibility of screw trajectory. Achieving a safe and feasible screw trajectory is the premise of this work. The screw placed should be completely wrapped by cortical bone in the trajectory but not pierce the cortical bone; meanwhile, the trajectory should have good operability in clinical practice. We defined the raised area of the lateral lamina where the inferior margin of the superior articular process of the vertebral body extends to the superior border of the inferior articular process of the same vertebral body as the outer crest of the vertebral lamina. In the design of the screw trajectory, different trajectories were obtained according to the different contact areas between the screw and cortical bone, with the different screw trajectories corresponding to different screw placement points. Then, we first considered whether the location of the entry point was safe and feasible, introducing the concept of a safe screw placement zone. The area jointly bound by the junctional zone of the inner inferior margin of the superior articular process, the superior border of the inferior articular process, the outer crest of the vertebral lamina, and the root of spinous process extending to the lamina were called the safe screw placement zone (Fig. 1). If the entry point was located outside the safe screw placement zone or if it was located in the safe screw placement zone but the screw punctured, the trajectory was excluded as not safe or feasible.

2.2.2. Sufficient contact volume of cortical bone in the screw trajectory. The CBT screw fixation strength mainly relies on the interfacial contact with cortical bone. In patients with osteoporosis, the trabecular density is significantly reduced, while the cortical bone is not significantly changed; thus, CBT screws could still provide effective fixation in patients with osteoporosis. Therefore, the contact volume between the cortical bone and CBT screws served as the main factor for evaluating the fixation strength. On the premise of a safe and feasible screw trajectory, the screw fixation strength was related to the contact volume of cortical bone in the screw trajectory; the larger the contact volume, the better the mechanical stability. Therefore, the ideal trajectory should ensure that the screw achieves contact with cortical bone over a sufficiently large volume.

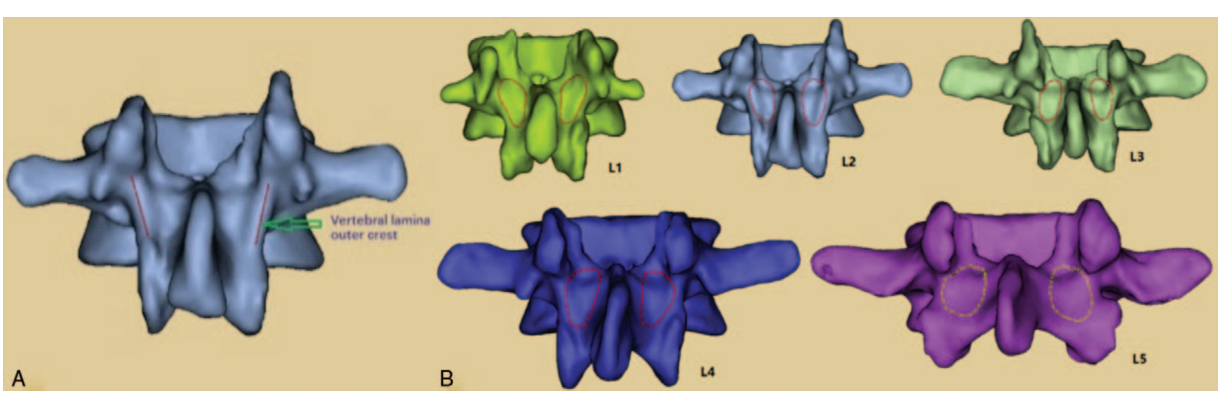

Figure 1. The area marked by the red line is the vertebral lamina outer crest of the left and right vertebral body (A). Schematic diagram of the safe screw placement zone for each lumbar segment (B).

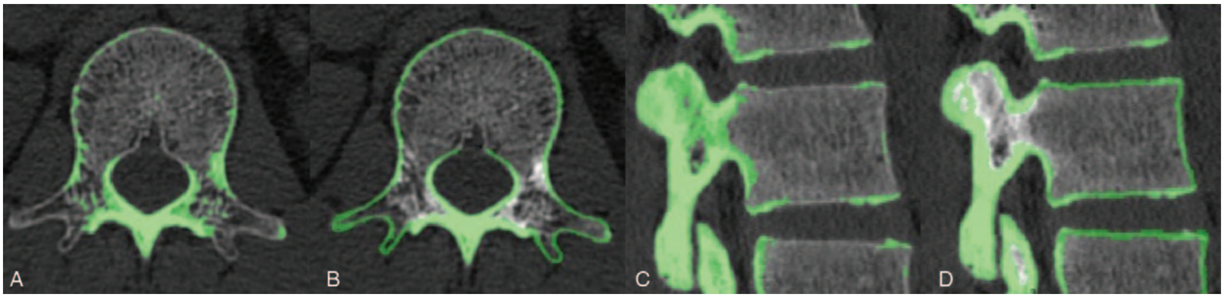

Figure 2. The excess cancellous bone in the transverse and sagittal planes was removed layer by layer using the Erase and Draw functions in Edit Masks, and the missing cortical bone was filled in; comparison between before treatment (AC) and after treatment (BD).

2.2.3. Sufficient screw diameter and length. The size of the screw trajectory would limit the size of the screw and is also the main basis for selecting the screw size. The contact volume between the cortical bone and the screw varies for screws of different sizes placed in the trajectory, leading to differences in fixation strength. Therefore, screw size is also an important factor affecting the fixation strength.

2.3. Method for designing the ideal trajectory

2.3.1. Establishment of three dimensions (3D) model of the lumbar spine. The CT data of 40 patients were imported into Mimics 19.0 software to load the tomographic information in Digital Imaging and Communications in Medicine (DICOM) format. By adjusting the threshold value of the images, surface contours of bone tissues in the images were formed to distinguish the bone and soft tissues. Since cortical and cancellous bone were often not clearly defined, excessive cancellous bone on the transverse and sagittal planes was removed layer by layer using the Erase and Draw functions, respectively, and missing cortical bone was subjected to manual refinement (Fig. 2). Then, the vertebral bodies were segmented one by one to reconstruct the vertebral cortical bone contour model (Fig. 3).

2.3.2. Establishment of the screw trajectory model. Taking the left vertebral pedicle as an example, the cortical bone of the vertebral pedicle was considered to have an elliptical cylindrical trajectory. The pedicle entry was the first point at which the screw entered the pedicle, and the other end of the pedicle was considered the pedicle exit point. According to the characteristics of CBT screw placement, the pedicle entry and exit sections were divided into 4 equal areas according to the horizontal and vertical directions, respectively. The entry of the pedicle was divided into zone A, in contact only with the inferior wall; zone B, in contact with both the inferior and medial walls; and zone C, in contact with the medial wall. The exit of the pedicle was divided into zone a, in contact with only the superior wall; zone b, in contact with the superior and lateral walls; and zone c, in contact with only the lateral wall. Nine different screw trajectories were designed for screws entering and exiting the area of contact with the vertebral pedicle: T-Aa, T-Ab, T-Ac, T-Ba, T-Bb, T-Bc, T-Ca, T-Cb, and T-Cc (Fig. 4). Then, screws with appropriate diameters were selected to simulate screw placement according to the requirements of the above 9 screw trajectories, and the relevant parameters of each screw trajectory were recorded.

2.3.3. Related parameters of screw trajectory. Cortical bone trajectory reference width (TRW): We selected the plain CT scan plane where the superior and inferior walls of the vertebral pedicle were highest in the cross-sectional image at the lumbar spine, drew a straight line parallel to the horizontal line of the vertebral body at the inner edge of the lateral wall of the vertebral pedicle, and a straight line parallel to the horizontal line of the vertebral body at the inner edge of the medial wall of vertebral pedicle; we then measured the vertical distance between the 2 straight lines (Fig. 5A). Because the anatomical structure of the pedicle of the L_5 vertebra was significantly different from that of the L_1–L_4 vertebrae, the L_5 vertebral body was defined separately in combination with the safety and feasibility of screw placement. The measuring plane was selected according to the above method, and the straight line (EF) at the narrowest point of the plane was drawn, which intersected with the inner edge of the lateral wall at point K. Then, the position of the outer crest of the vertebral lamina on the cross-section was determined to be represented by point G. Then, point G was connected to point K, and a straight line parallel to the line GK was drawn such that it shifted to the medial side and just contacted the inner edge of the medial wall. Finally, the vertical distance between the 2 parallel lines was measured (Fig. 5B).

Cortical bone trajectory reference height (TRH): We selected the plain CT scan plane with the largest height between the superior and inferior walls of the vertebral pedicle on sagittal scans of the lumbar spine, and we drew a straight line parallel to the superior border of the vertebral body at the superior border of the inferior wall of the vertebral pedicle and a straight line parallel to the superior border of the vertebral body at the inferior margin of the superior wall of the vertebral pedicle; we then measured the vertical distance between the 2 straight lines, namely, the TRH (Fig. 5C).

Cephalad angle (A): The cephalad angle is formed by the central axis of the screw and the endplate of the vertebral body on the sagittal plane (Fig. 5D).

Lateral angle (B): The lateral angle is the angle at which the head-end of the screw deviates from the horizontal line of the vertebral body on the transverse plane (Fig. 5E).

Screw trajectory diameter (D): This diameter is the diameter of the simulated screw.

Length of screw trajectory (L): This parameter is the distance between the centers of the head-end and tail-end sections of the cylindrical model of the screw trajectory.

Coupling capacity (V): This parameter is the volume of the mutual gomphosis of the screw and cortical bone for each screw trajectory, which could indirectly reflect the contact volume of cortical bone in the screw trajectory (Fig. 5F).

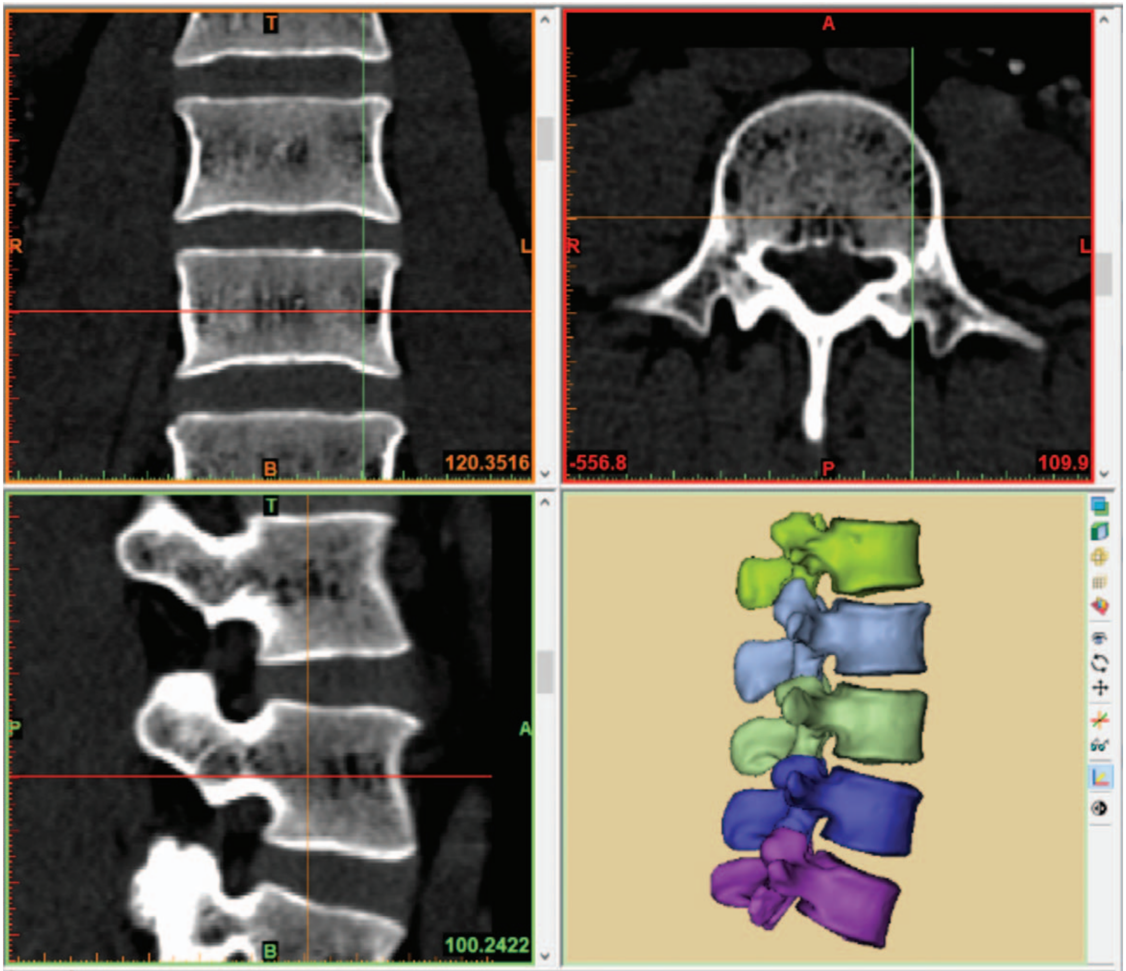

Figure 3. All lumbar segments were segmented one by one using the segmentation module, followed by reconstruction of the contour model of the lumbar cortical bone.

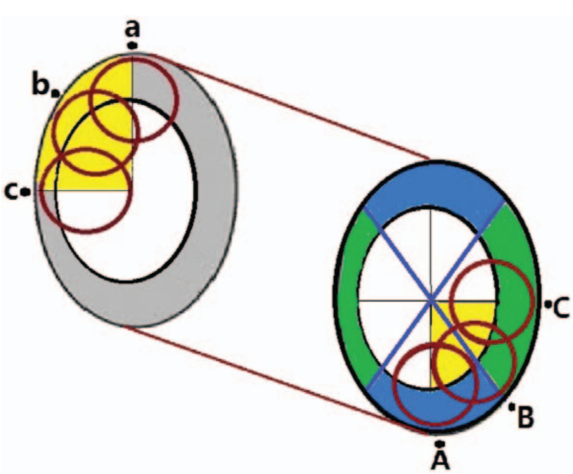

Figure 4. A schematic diagram of the pedicle channel, using the left pedicle as an example: the blue areas are the superior and inferior walls of the pedicle, the green areas are the interior and exterior walls of the pedicle, and the yellow areas are the areas of screw contact at the entry and exit. According to the different screw contact areas, 9 different screw trajectories were obtained: T-Aa, T-Ab, T-Ac, T-Ba, T-Bb, T-Bc, T-Ca, T-Cb, and T-Cc.

2.4. Screw size selection

2.4.1. Selection of screw diameter. The contact volume between the cortical bone and screws differed for screws of different diameters placed in the same screw trajectory. Therefore, the screw diameter would affect the fixation strength. Two parameters were introduced in combination with the characteristics of CBT screw placement, namely, the TRW and TRH. Since the height of the vertebral pedicle was greater than the width, the TRW was the main factor limiting the screw diameter. When TRW < 4.0 mm, the pedicle was very narrow, and the screw could extremely easily pierce the cortical bone in the screw trajectory; thus, the placement of this screw was not recommended. When 4.0 mm ≤ TRW < 4.5 mm, a screw with a diameter of 4.0 mm was recommended; when 4.5 mm ≤ TRW < 5.0 mm, a screw with a diameter of 4.5 mm was recommended; when 5.0 mm ≤ TRW < 5.5 mm, a screw with a diameter of 5.0 mm was recommended; when 5.5 mm ≤ TRW, a screw with a diameter of 5.5 mm was recommended (Table 1).

2.4.2. Selection of screw length. When a suitable screw trajectory was designed, the center of the tail-end section of the screw trajectory was just in contact with the dorsal cortex of the vertebral body, and the head-end of the screw trajectory was just

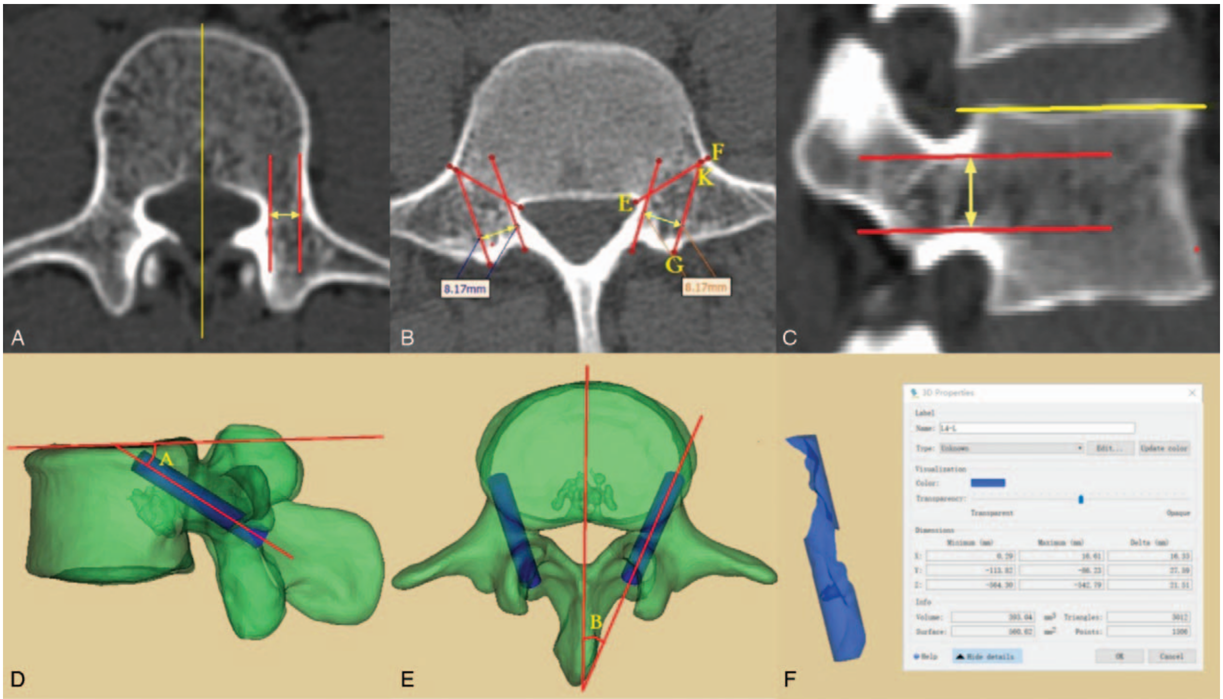

Figure 5. Schematic diagram of TRW (L_1–L_4, A; L_5, B); schematic diagram of TRH (C); schematic diagram of the cephalad angle and the lateral angle (D and E); Boolean operations were performed on the simulated screw to obtain the coupling capacity (F).

in contact with but did not pierce the upper end plate. At this time, the distance between the centers of the sections at both ends of the screw trajectory was defined as the length of the screw trajectory (Fig. 6).

2.5. Related factors influencing the ideal trajectory

2.5.1. Rate of placement for the screw trajectory. The placement of all vertebral pedicles was simulated according to the requirements of the corresponding screw trajectories, and then the number of vertebral pedicles corresponding to the requirements of the screw trajectory for each lumbar segment as a percentage of the total number of vertebral pedicles in the included data was calculated, namely, the placement rate for the screw trajectories corresponding to the pedicles was calculated. The rate of placement was indicated by a percentage, which was an important index for evaluating the quality and safety of screw placement. The higher the screw placement rate, the more reliable and safer the placement of screws in that trajectory. In the design of the ideal screw trajectories, we considered a placement rate ≥85% as the basic condition for an ideal screw trajectory.

Table 1

Relationship between the TRW and the diameter of the screw trajectory.

TRW group	4.0 mm	4.5 mm	5.0 mm	5.5 mm
TRW < 4.0 mm	×	×	×	×
4.0 mm ≤ TRW < 4.5 mm	√	×	×	×
4.5 mm ≤ TRW < 5.0 mm		√	×	×
5.0 mm ≤ TRW < 5.5 mm			√	×
5.5 mm ≤ TRW				√

TRW = trajectory reference width.

2.5.2. Screw trajectory and screw length. When the screw trajectory length (L) was less than 20 mm, the placement of a 20 mm screw was likely to pierce the cortical bone in the screw trajectory, thereby increasing the risk of surgery. Considering the clinical safety of screw placement, screw trajectories with $L < 20$ mm were excluded. When 20 mm ≤ L < 25 mm, a screw 20 mm in length was recommended; when 25 mm ≤ L < 30 mm, a screw 25 mm in length was recommended; when 30 mm ≤ L < 35 mm, a screw 30 mm in length was recommended; when L ≥ 35 mm, a screw 35 mm in length was recommended (Table 2).

2.5.3. Screw trajectory length, screw length, and coupling capacity. When the length of the screw placed was equal to the length of the screw trajectory, the coupling capacity of the screw was equal to the coupling capacity of the screw trajectory. When the length of the screw placed was less than the length of the screw trajectory, the coupling capacity of the screw was less than the coupling capacity of the screw trajectory. The greater the difference between the screw length and the screw trajectory length within a certain range, the less the coupling capacity of the screw. Therefore, when comparing the cortical bone contact volume of screws between 2 screw trajectories, not only the coupling capacity of the actual measured screw trajectory but also the difference between the screw length and the screw trajectory length should be taken into consideration to evaluate the contact volume between the cortical bone and the actual placed screw.

2.5.4. Screw size and trajectory angle. Screw length is another important factor in the design of the ideal trajectory. When other factors are equivalent or similar, the longer the screw length, the better the fixation strength; the larger the cephalad angle, the more easily the screw can loosen, and the more difficult the screw

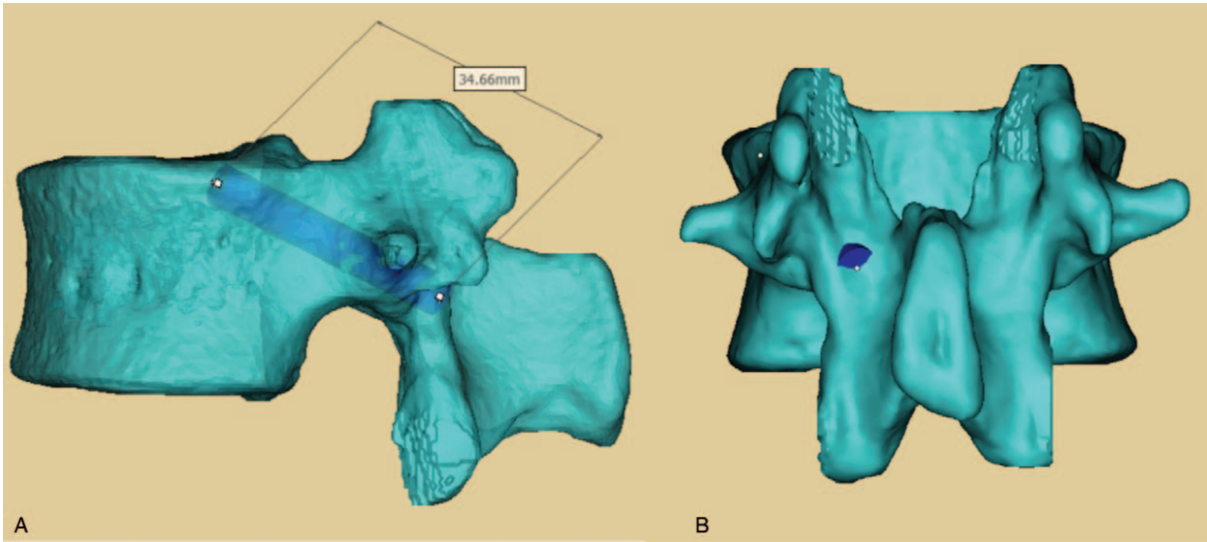

Figure 6. The center of the cross-section just contacted the dorsal cortex of the entry point (A). The head side of the screw trajectory just contacted the upper endplate but did not pierce it; the distance between the centers of the sections at both ends of the screw trajectory was determined as the length of the screw trajectory (B).

is to install; the larger the lateral angle, the more vulnerable the spinous process is to blocking. Therefore, the angle of the screw trajectory is also a factor in selecting the ideal screw trajectory.

2.6. Determination of the ideal screw trajectory

After simulating the screw placement, the relevant parameters of the screw trajectory were recorded and analyzed statistically. Under the premise of safety and feasibility, we considered a placement rate ≥85% as the basic condition for the ideal screw trajectory. The coupling capacity was the main reference for determining the ideal screw trajectory. Based on a comprehensive analysis of the primary and secondary relationships among the ideal screw trajectory length, screw length and coupling capacity, and between the screw placement angle and clinical operability, the ideal screw trajectory was finally selected. Finally, the CBT screw entry point for each lumbar segment was deduced according to the optimal screw trajectory. The location of the screw entry point is described according to the relation between the location of the entry point and the dorsal anatomical landmarks of the vertebral body.

2.7. Clinical verification of screw placement based on the ideal trajectory

The study was in line with the Helsinki Declaration and was approved by the Institutional Review Board (IRB) of the Chinese People's Liberation Army Joint Service Support Force 920 Hospital. All patients received informed consent and signed a consent form. A total of 23 inpatients, including 9 males and 14 females, with a mean age of 56.3 ± 8.1 years (range, 42–70 years) were selected from our hospital; all patients had received treatment with posterior canal decompression and internal fixation for intervertebral fusion with CBT screw technology. To improve the quality and accuracy of screw placement, we adopted screw drilling template navigation technology to assist CBT screw placement. Before surgery, Mimics 19.0 software was used to perform 3D reconstruction of the CT data of the patients, and the orientation of the guide tube was determined according to the characteristics of the optimal screw trajectory of the corresponding lumbar segments. Then, according to the bony anatomical structure on the surface of the template domain, the template was designed and accurately matched with the guide tube to generate a navigation template for screw placement. Finally, a 3D printer was used to print the real navigation template, and a photocuring treatment was carried out to enhance the physical performance of the template. Preoperatively, the navigation template was disinfected by low-temperature plasma to assist in intraoperative CBT screw placement.

Table 2

Relationship between the screw trajectory length and the actual screw length.

Length of screw trajectory	20 mm	25 mm	30 mm	35 mm
$L < 20$ mm	×	×	×	×
20 mm ≤ $L < 25$ mm	√	×	×	×
25 mm ≤ $L < 30$ mm		√	×	×
30 mm ≤ $L < 30$ mm			√	×
$L \geq 35$ mm				√

2.8. Statistical analysis

SPSS 21.0 statistical software was used, and all measurement data are represented by $\bar{x} \pm s$. Student's t test was used to compare various indexes between groups, and differences with $P < .05$ were considered statistically significant. The rank-sum test was used to compare nonnormally distributed data, which are represented by the median (interquartile range) [M (Q)].

3. Results

3.1. Ideal CBT screw trajectory for each lumbar segment

Screw trajectories with a placement rate for the corresponding lumbar segment ≥85%: T-Bb, T-Bc, T-Cb, and T-Cc were satisfactory for L_1; T-Bb, T-Bc, T-Cb, and T-Cc for L_2; T-Bb, T-Cb, and T-Cc for L_3; T-Bb for L_4; and T-Bb and T-Bc for L_5. As

Table 3

Screw trajectory parameters with a screw placement rate at each lumbar segment ≥ 85%.

Screw trajectory	Rate of placement	Coupling capacity	Screw trajectory length	Cephalad angle	Lateral angle
L_1 T-Bb	100.00%	348 (154)	33.19 ± 1.93	46.18 ± 3.62	24.35 ± 6.59
T-Bc	100.00%	318 (167)	35.39 ± 2.09	37.33 ± 3.94	22.16 ± 4.25
T-Cb	100.00%	306 (376)	27.70 ± 2.11	35.82 ± 5.07	24.42 ± 6.42
T-Cc	100.00%	233 (91)	33.88 ± 2.77	27.25 ± 7.47	21.04 ± 4.71
L_2 T-Bb	85.71%	417 (196)	33.53 ± 3.02	44.24 ± 3.60	24.87 ± 3.51
T-Bc	85.71%	351 (158)	34.15 ± 2.51	34.02 ± 2.74	21.62 ± 3.15
T-Cb	100.00%	288 (152)	28.52 ± 3.29	33.98 ± 6.22	20.39 ± 7.05
T-Cc	100.00%	250 (90)	32.45 ± 1.95	25.78 ± 5.91	20.45 ± 3.37
L_3 T-Bb	88.57%	421 (251)	32.35 ± 2.65	41.94 ± 3.05	20.69 ± 3.20
T-Cb	100.00%	295 (206)	29.02 ± 3.32	33.82 ± 5.11	19.05 ± 7.94
T-Cc	88.57%	243 (205)	34.29 ± 3.27	24.68 ± 4.12	17.69 ± 4.87
L_4 T-Bb	89.47%	363 (226)	31.56 ± 4.20	32.09 ± 2.54	19.25 ± 3.75
L_5 T-Bb	90.00%	410 (330)	31.17 ± 6.05	26.58 ± 9.94	20.07 ± 6.53
T-Bc	85.00%	362 (259)	32.94 ± 4.32	26.49 ± 3.84	19.63 ± 4.54

a screw placement rate ≥85% was the basic condition for a trajectory to be included as an optimal screw trajectory for the lumbar spine, trajectories with a placement rate <85% were excluded when statistical analysis of the screw trajectories parameters was performed.

Relevant parameters corresponding to trajectories with a placement rate for each lumbar segment ≥85%, as shown in Table 3: among them, T-Bb, T-Bc, T-Cb, and T-Cc were satisfactory for the L_1 segment. First, analysis of the T-Bb and T-Bc screw trajectories showed a length of 33.19 ± 1.93 mm and 35.39 ± 2.09 mm, respectively, and a coupling capacity of 348 (154) mm^3 and 318 (167) mm^3, respectively. According to the relationship between the length of the screw trajectory and the screw, CBT screws 30 mm and 35 mm in length were selected for the T-Bb and T-Bc screw trajectories, respectively, during the actual screw placement. When the screw length was less than the length of the screw trajectory, the actual contact volume of cortical bone was less than the measured cortical bone volume. The greater the difference between the screw length and the length of screw trajectory, the less the cortical bone contact volume. The actual length of the screw (30 mm) placed in the T-Bb screw trajectory was significantly smaller than that of the screw trajectory (33.19 mm). Therefore, the contact volume between the screw and the cortical bone was significantly less than the contact volume between the cortical bone and the screw trajectory. The actual length of the screw (35 mm) placed in the T-Bc screw trajectory was approximately equal to that of the screw trajectory (35.39 mm). Therefore, the volume of contact between the cortical bone and the screw was comparable to that between the cortical bone and the screw trajectory. According to the analysis of the parameters of T-Bb and T-Bc above, there was no significant difference in the cortical bone contact volume between the 2 screw trajectories. However, the screw length (35 mm) in the T-Bc screw trajectory was larger than that in the T-Bb screw trajectory (30 mm). The cephalad angle (46.18 ± 3.62) of the T-Bb screw trajectory was significantly higher than that of the T-Bc screw trajectory (37.33 ± 3.94), while the lateral angles were similar (24.35 ± 6.59, 22.16 ± 4.25). During screw placement, the inclination between the T-Bb screw trajectory and the dorsal cortex was too large, so the operability of screw placement was not as good as that for the T-Bc screw trajectory. Therefore, T-Bc was generally superior to T-Bb after a comprehensive analysis. Finally, the optimal screw trajectory for L_1 was finally determined to be T-Bc after the T-Bc, T-Cb, and T-Cc screw trajectories were compared and analyzed. Analysis showed that T-Bc and T-Bb were the ideal trajectories for L_2 and L_3–L_5, respectively.

Entry point of lumbar CBT screws: Through comparative analysis, we found that the location of the entry point was relatively stable compared with the position of the outer crest of the vertebral lamina and the joint of the articular process. The positional relation was as follows: the entry point was located at the intersection of the inner 1/3 vertical line of the joint of the superior articular process and the horizontal line at the lower 1/3 of the outer crest of the vertebral lamina, namely, 2 to 4 mm inward at the lower 1/3 of the outer crest of the vertebral lamina. The relative location of the entry point and the projection of the pedicle could be observed by adjusting the transparency of the vertebral body. The volume of cortical bone contact in the screw trajectory could be determined by lateral projections and cross-sections to determine the screw trajectory. The cephalic end of the screw trajectory was located approximately 1/4 to 1/3 behind the upper endplate of the vertebral body (Fig. 7).

3.2. Relevant parameters of the ideal trajectory

The TRW in the L_1–L_5 pedicles gradually increased (4.14 ± 1.07 mm to 7.13 ± 1.16 mm) and were largest for L_4. For L_1–L_5, the screw trajectory length was 31.56 ± 4.20 mm to 35.39 ± 2.09 mm, the cephalad angle was 26.49 ± 3.84 mm to 41.94 ± 6.05 mm, and the lateral angle was 19.63 ± 4.54 mm to 22.16 ± 4.25 mm, as shown in Table 4. Although the TRH at all lumbar segments decreased gradually and the TRW increased gradually, the TRWs of L_1–L_5 were all smaller than the TRH, indicating that the TRW is an important parameter for selecting the screw diameter. According to the relevant parameters of each screw trajectory and the relationship between the size of the screw trajectory and that of the screw, the reference screw diameter and length selected for each lumbar segment was as follows: L_1, 4.0 mm and 35 mm; L_2, 4.5 mm and 30 mm; L_3, 5.5 mm and 30 mm; L_4, 5.5 mm and 30 mm; and L_5, 5.5 mm and 30 mm, respectively, as shown in Table 5.

3.3. Clinical verification of screw placement based on the ideal screw trajectory

In this study, there were 15 patients with spinal stenosis, 3 patients with lumbar spondylolisthesis, and 5 patients with

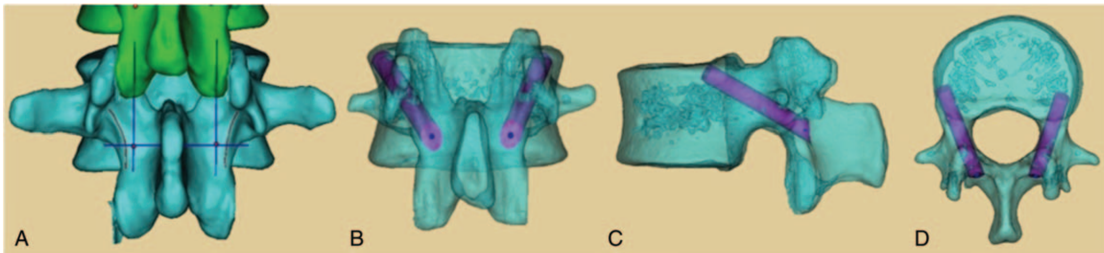

Figure 7. Diagram of the lumbar CBT screw entry point location: at the intersection of the inner 1/3 vertical line of the superior facet joint and the bottom 1/3 horizontal line of the outer crest of the vertebral lamina (A). The positional relationship between the screw and the vertebral pedicle shown in the anteroposterior (B), lateral (C), and cross-sectional (D) views after adjustment of the transparency of the vertebral body.

intervertebral disc protrusion. The number of fixed lumbar spine segments was as follows: L_1*0, L_2*1, L_3*2, L_4*18, and L_5*21. A total of 84 CBT screws were placed, and there were no abnormal conditions, such as insufficient screw holding force, screw placement failure, screw trajectory splitting, or blood vessel or nerve injury. The patients were followed up for 24.0 ± 6.6 months (range, 12–36 months), during which there were no adverse events occurred, such as screw loosening, unscrewing, nut slipping, or screw fracture, in any patient during the postoperative follow-up period, and the internal fixation instrumentation and intervertebral fusion cage of the screw rod system remained in good positions.

4. Discussion

CBT screw technology has been clinically applied as it continues to develop. The CBT screw is small in diameter and short in length, but the thread arrangement is tight, which increases the contact interface between the screw and cortical bone, thus enhancing the holding force of the screw. After analyzing the parameters of L_4 and L_5 segments treated using CBT screw technology and traditional pedicle screw technology based on the CT data of 222 patients, Kojima et al[8] found that the values of the CBT screws determined by were nearly 4 times higher than those of the traditional screws. This conclusion is consistent with the view held by most surgeons that "cortical bone screws can provide holding force mainly based on the interface contact between the screw and cortical bone."[7,9,10] In addition, if the entry point of the CBT screw is closer to the interior, it could allow a smaller surgical incision, reduced soft tissue dissection, reduced bleeding, and faster postoperative recovery.[11,12] The specific orientation of the screw trajectory can also reduce the probability of vascular and nerve injury.[13]

Nevertheless, in recent years, this technology has not been used in the clinic rapidly or widely, mainly due to the high technical requirements, long learning curve, and lack of uniform standards for screw placement and screw size. Deviations in the screw placement angle or improper selection of the screw size will lead to weakening of the fixation strength, splitting of the screw trajectory, or even neurovascular injury. In 2013, Matsukaw et al[13] reported positioning of the entry point of the CBT screw in the lumbar spine at the intersection of the vertical line of the superior articular process and the horizontal line 1 mm below the inferior margin of the transverse process. The average screw diameter for L_1–L_5 increased gradually (6.2 ± 1.1 mm to 8.4 ± 1.4 mm), the average screw length for L_1–L_4 increased gradually (36.8 ± 3.2 mm to 39.8 ± 3.5 mm), and the screw length in L_5 (38.3 ± 3.9 mm) was similar to that in L_2 (38.2 ± 3.0 mm). There were no obvious differences among L_1–L_5 in the lateral angle (8.6 ± 2.3°, 8.5 ± 2.4°, 9.1 ± 2.4°, 9.1 ± 2.3°, 8.8 ± 2.1°) or the cephalad angle (26.2 ± 4.5°, 25.5 ± 4.5°, 26.2 ± 4.9°, 26.0 ± 4.4°, 25.8 ± 4.8°). Meanwhile, the use of an intraoperative anterior lumbar film was also proposed to treat the projection of the pedicle as a dial plate, with the left screw pointing from 5 o'clock to 11 to 12 o'clock and the right screw pointing from 7 o'clock to 12 to 1 o'clock. The advantage of this method was that the fixation point was not disturbed by the position of the facet joints and could still be used as a reference when the joints were broken and separated. However, this method was too ambiguous, and repeated fluoroscopy was required during the operation. Additionally, there was a certain spatial distance between the pedicle projection and the screw placement point, so it was difficult to accurately determine the position and direction of screw placement. In 2014, Iwatsuki et al[14] proposed an isthmus-guided screw placement method: the screw placement point was located at the outer edge of the isthmus 3 mm toward the inside, lateral lumbar X-rays were used during the operation, and the screw was located at the superior margin of the intervertebral foramen. In this method, the entry point was closer to the cephalic side, and the screw placement direction was the same as that of the original CBT screw. As the screw was far from the intervertebral foramen, the occurrence of nerve root injury caused by the screw straying into

Table 4

Ideal screw trajectory parameters for each lumbar segment.

Screw trajectory	Screw trajectory width	Screw trajectory length	Cephalad angle	Lateral angle
L_1-Bc	4.14 ± 1.07	35.39 ± 2.09	37.33 ± 3.94	22.16 ± 4.25
L_2-Bc	4.65 ± 0.92	34.15 ± 2.51	34.02 ± 2.74	21.62 ± 3.15
L_3-Bb	5.78 ± 0.94	32.35 ± 2.65	41.94 ± 3.05	20.69 ± 3.20
L_4-Bb	7.13 ± 1.16	31.56 ± 4.20	32.09 ± 2.54	19.25 ± 3.75
L_5-Bb	6.56 ± 0.97	32.94 ± 4.32	26.49 ± 3.84	19.63 ± 4.54

Table 5

Reference size of CBT screw for ideal screw trajectory.

Lumbar segment	Screw diameter	Screw length
L_1	4.0 mm	35 mm
L_2	4.5 mm	30 mm
L_3	5.5 mm	30 mm
L_4	5.5 mm	30 mm
L_5	5.5 mm	30 mm

CBT = cortical bone trajectory.

Table 6

CBT screws of different sizes for the lumbar spine reported in the literature.

Years	Author	Screw diameter	Screw length
2009	Santoni et al[7]	4.66 ± 0.24 mm	29.00 ± 2.89 mm
2013	Perez-Orribo et al[15]	4.5 mm	25–30 mm
	Mobbs[16]	5.0–5.5 mm	25–30 mm
	Ueno et al[17]	4.5 mm	25–30 mm
2014	Matsukawa et al[18]	5.5 mm	30–35 mm
	Baluch et al[19]	4.5 mm	31.88 ± 4.03 mm
	Rodriguez et al[20]	5.5 mm	30–35 mm
	Mizuno et al[21]	4.5–5.5 mm	25–30 mm
	Iwatsuki et al[14]	4.5 mm	25 mm
2015	Calvert et al[22]	4.5 mm	30 mm
	Ueno et al[23]	4.5 mm	25 mm
	Lee et al[24]	5.5 mm	30 mm
2016	Matsukawa et al[25]	5.5 mm	35 mm
2019	Our research	4.0–5.5 mm	30–35 mm

CBT = cortical bone trajectory.

the intervertebral foramen was also reduced. However, the screw placed was relatively short, and the holding force of the screw was reduced accordingly.

A review of the literature showed that the size of CBT screws used in the lumbar spine also varies significantly (Table 6). Currently reported CBT screws for lumbar spine, diameter: 4.5 to 5.5 mm, length: 25 to 35 mm.[7,14,15–25] And our research results show that: diameter 4.0 to 5.5 mm, length: 30 to 35 mm. The selection of the screw placement point and the angle and size of the screw trajectory will affect the screw size and the contact volume between the cortical bone and the screw, thus affecting the fixation strength of the screw. Therefore, differences in the lumbar CBT screw size are mainly caused by differences in the screw placement method. Different screw placement methods will produce different screw trajectories, and the contact volume of cortical bone of different screw trajectories will inevitably be different, thereby leading to different fixation strengths. Therefore, there must be an ideal screw trajectory that is safe and feasible and can fully guarantee the screw fixation strength.

According to the characteristics of CBT screw placement, we designed 9 different screw trajectories in contact with the cortical bone through the pedicle entry and exit points. The ideal screw trajectory was not determined in advance but was instead based on a comprehensive analysis of the safety and feasibility of screw placement, the cortical bone contact volume, and the screw trajectory parameters; the ideal screw trajectory among the 9 screw trajectories was finally determined. Meanwhile, we did not define the location of the entry point in advance because each trajectory corresponded to a different entry point, and the fixed entry points did not adapt to all screw trajectories. After the screw trajectory was determined, the location of the entry point was deduced through the positional relationship between the screw trajectory and the dorsal cortex. When selecting the screw size, we did not choose the same standard size but instead introduced the TRW parameter. Since the TRW was the main factor limiting the screw diameter, we selected the corresponding screw diameter according to the measured TRW before simulating the screw placement. Thus, deviations in the final results caused by the lack of a uniform standard in selecting the diameter of the simulated screw were avoided.

In this study, screw placement in different screw trajectories was simulated with digital technology, which provides the advantages of good repeatability, clear and reliable screw trajectories, and simple and convenient measurement of the screw trajectory parameters; however, we could not directly calculate the cortical bone contact volume of the screw trajectory. To quantify this index, we introduced the concept of coupling capacity. We could calculate the coupling capacity via Boolean operations. To minimize errors, we manually adjusted image thresholds to identify bone and soft tissue in the reconstructed lumbar spine model. Since the interface between the cortical and cancellous bone could not always be fully defined, segmentation and reconstruction were performed after excess cancellous bone in the transverse and sagittal planes was removed layer by layer. The missing cortical bone was then filled in using the Erase and Draw functions. It was assumed that the cortical bone contact volume of the screw trajectory could be considered approximately the interface area between the screw and cortical bone in the screw trajectory. The cortical bone contact volume increased with increasing coupling capacity. Although the relationship between the 2 was not linear, it could indirectly reflect differences between different screw trajectories within the same pedicle. Therefore, we chose the coupling capacity as the parameter for analyzing the cortical bone contact volume of the screw trajectories.

To better determine the reliability of the screw trajectory, we also introduced the concept of the screw placement rate. The screw placement rate is an important index for evaluating the quality and safety of screw placement. The higher the screw placement rate, the more reliable and safer the screw placement of the screw trajectory. When designing the optimal cortical bone screw trajectory, we considered a screw placement rate ≥85% as the basic condition for an optimal screw trajectory. Finally, based on a comprehensive analysis of the primary and secondary relationships, the ideal screw trajectory corresponding to the L_1–L_5 vertebrae was obtained according to the safety, feasibility, screw placement rate, coupling capacity, and relevant parameters of the screw trajectory, among other factors. The T-Bc trajectory was ideal for L_1 and L_2, that is, the screw reached the upper endplate of the vertebral body from the dorsal cortex through the inner inferior wall of the pedicle entry segment, the outer wall of the exit segment, and the lateral wall of the vertebral body. The T-Bb trajectory was ideal for L_3, L_4, and L_5, that is, the screw reached the upper endplate of the vertebral body from the dorsal cortex through the inner inferior wall of the pedicle entry segment, the outer superior lateral wall of the exit segment, and the lateral wall of the vertebral body. Then, according to the screw trajectory, we deduced the position of the entry point. Through a comparative analysis of the different samples, the entry point was found to be relatively stable compared with the position of the outer crest of the vertebral lamina and the articular process. The entry point was located at the intersection of the inner 1/3 vertical line of the superior facet joint and the bottom 1/3 horizontal line of the outer crest of the vertebral lamina (i.e., 2–4 mm inward at the bottom 1/3 of the outer crest of the vertebral lamina).

Finally, we further verified the safety and feasibility of the trajectories through clinical application based on the ideal trajectories. In the clinical screw placement process, there were no abnormal conditions, such as insufficient screw holding force, screw placement failure, screw trajectory splitting, or blood vessel or nerve injury. No adverse events occurred, such as screw loosening, screw pullout, nut slipping, or screw fracture, in any patient during the postoperative follow-up period.

5. Conclusions

In summary, the ideal screw trajectory for L_1–L_2 is the T-Bc, the screw diameter, and length (L_1: 4.0 mm, 35 mm; L_2: 4.5 mm, 30 mm). The ideal screw trajectory for L_3–L_5 is T-Bb, the screw diameter is 5.5 mm, and the length is 30 mm. CBT screw placement based on ideal screw trajectory is a safe and reliable method, which can achieve effective fixation and satisfactory postoperative results. However, this study needs further biomechanical research and more clinical application verification.

Author contributions

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