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CLINICAL ARTICLE

Comparison of Different Insertion Techniques for Lumbosacral Fixation Improvement: A Finite Element Study

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Objective: We create a new S1 cortical screw trajectory technique using 3D reconstruction and the finite element (FE) method to provide a more reliable theoretical basis for clinical practices and to advance internal fixation technology for treatment of lumbosacral degenerative diseases.

Methods: This retrospective study included patients (aged from 40 to 70 years) who needed intervertebral fusion surgery between August 2016 and August 2017. Data of patients with lumbosacral lesions was scanned and measured by 64-row spiral CT, and were then transmitted to the GE-AW4.3 post-processing system for 3D reconstruction. The trajectories of the three different screws were simulated by FE software and processed by mimics software to simulate the screw path: traditional PS fixation (Model A); traditional cortical screw (Model B); and new cortical screw (Model C). The CT value of the bone around the screw canal was recorded. Biomechanical effects of the three screws were analyzed and compared.

Results: The displacement of flexion and extension, the vertebral body stress of right torsion, and the cage stress of flexion showed no significant differences among the three models ($P > 0.05$). The results demonstrated that cortical screws exceeded pedicle screws in stability and pullout force. Models B and C showed higher vertebral displacement in left bending (0.41 and 0.31 mm) and right bending (0.58 and 0.40 mm), lower vertebral body stress on extension (48.37 and 38.92 MPa), left bending (0.76 and 0.74 mm) and right bending (0.50 and 0.53 mm), and higher cage stress on left bending (162.19 and 160.63 MPa), right bending (150.02 and 150.05 MPa), left torsion (158.45 and 146.27 MPa) and right torsion (167.33 and 171.15 MPa) (all $P < 0.05$) compared to model A. Compared to Model B, Model C had higher displacement of left and right torsion, lower pressure in extension and flexion, and lower stress on cages in extension ($P < 0.05$).

Conclusion: The new cortical screw insertion method has similar effects to traditional cortical screw fixation. However, it demonstrated advantages in promoting lumbosacral interbody fusion, which protects vessels and nerves.

Key words: Cortical bone trajectory; Finite element method; Insertion technique; Lumbosacral fixation; Pedicle screw

Introduction

Lumbar degenerative diseases commonly occur in elderly patients, and patients usually undergo a general surgical procedure, lumbosacral fusion. The decision to fuse lumbar segments depended on the instability as well as the severity of degeneration. The goals of the lumbosacral fusion procedure are to relieve the symptoms and strengthen the segment[1].

Traditionally, pedicle screw (PS) fixation, first introduced by Boucher in 1959[2] and then popularized by Roy-Camille in the 1960s[3], was the gold standard treatment for lumbar spine disease, including degeneration, trauma, neoplasms and deformity. This is a traditional insertional pathway that allows the screw to be punctured from the junction between the lateral wall of the facet and the transverse process,

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across the pedicle axis to the vertebral body[3]. It can be applied to fix the metal plates for spine support. However, this technique is challenging and is associated with high risks of nerve, blood vessel, and mechanical injury[4–6]. Especially in patients with osteoporosis, the diminished fixation strength of the screws and increased rates of loosening limit the application of PS in osteoporotic vertebrae[7,8].

The cortical bone trajectory (CBT) screw is a novel PS trajectory technique invented by Santoni *et al.* that increases the bone–screw contact[9]. It maximizes the pullout strength to reduce surgical complications such as soft tissue injury, and, therefore, decreases morbidity rates[10]. The screw in this method punctured the mediolateral path or the caudocephalad path in the axial plane and the sagittal plane, respectively[9]. This technique does not require much muscular exposure and, therefore, involves relatively less damage[7].

Compared with the traditional PS instrumentation, the starting point of the CBT is lower and deeper. It has the characteristics of minimal trauma[11], lower blood loss[12], and more pullout force[13], providing an alternative method for osteoporosis and surgical revision for instrumented lumbar spinal surgery. However, the insertion technique of S1 cortical screws has rarely been analyzed in the literature as a discrete entity. Now the main sticking point regarding the S1 screw trajectory is how to select an optimum starting point.

The starting point of the traditional S1 pedicle screw technique is on the junction point of the vertical line from the lateral margin of the S1 articular process and the horizontal line from the inferior margin of the articular process. The direction of the screw is parallel to the S1 endplate. The far end of the screw terminates at the anterior sacral cortex and does not penetrate the anterior sacral cortex[14]. Unlike the conventional PS method, the current method is used to obtain a more medial entry point, such as the S1-alar screw (S1AS) trajectory, which is directed 30° lateral and 30° distal[15]. In 2014, Matsukawa *et al.*[14] introduced another sacral pedicle screw trajectory, the "penetrating S1 endplate screw" (PES). The starting point for the PES was located at the junction of the center of the superior articular process of S1 and nearly 3 mm inferior to the most inferior border of the inferior articular process of L5[14]. The PES is significantly more stable against loosening and has a higher pullout resistance compared to the S1AS trajectory[15,16]. However, it is still unclear whether this technique would affect the intervertebral fusion.

To determine a more suitable insertion technique, we create a new S1 cortical screw trajectory technique using 3D reconstruction and the finite element (FE) method. The trajectory of the traditional S1 pedicle screw, the traditional S1 cortical screw and the new S1 cortical screw were simulated based on reconstructed data to provide a theoretical basis for the application of S1 pedicle cortical screw fixation.

Materials and Methods

Establishment of the Intact L5–S1 Segment Model

This is a retrospective study that investigates the sacral trajectory insertion technique using the FE method. We included patients aged from 40 to 70 years who had CT scans between August 2016 and August 2017 at Shandong Provincial Hospital and Shandong Province Hospital affiliated to Shandong University. The study received approval from the ethics committee of our hospital and all patients gave signed informed consent.

A 3D FE model of L5–S1 was developed using MIMICS software according to the method reported by Xiao *et al.*[17] Geometrical details of all the parts in the model were obtained from CT images of patients. The CT images of the L5–S1 vertebrae were transmitted into the MIMICS software in DICOM format, and the appropriate gray scales were adjusted to obtain clear bone contours. After the mask process, the files were exported into STL format. Then the STL files were transferred into Geomagic software for reconstruction. Finally, the encapsulation surface was materialized to generate a 3D graphic IGES file format. Once the bone contours were successfully established, the structures such as the intervertebral disc and the facet joint were built using Solidworks software, and then transferred into the Ansys Workbench 18. The model is shown in Fig. 1.

Establishment of the Surgical Models

On the basis of the normal model, the L3–L4 intervertebral disc was excised and implanted with a cage, as shown in Fig. 2.

Traditional PS fixation (Model A), traditional cortical screw fixation (Model B), and the new cortical screw fixation (Model C) were modeled in SOLIDWORKS software, as shown in Fig. 3.

Contact, Boundary, and Loading Conditions

To validate the model, the effect of body weight on the dynamic performance of lumbosacral vertebrae should be taken into consideration. Therefore, we added a quantity of 50 kg into the L1 lumbar vertebra. Six degrees of freedom of the sacrum and pelvis contact were restrained. Pure unconstrained 10 Nm extension (e), 10 Nm flexion (f), 10 Nm lateral bending (l), and 10 Nm torsion (t) moments were applied to the superior surface of the L5 vertebral body according to Xiao's method[17].

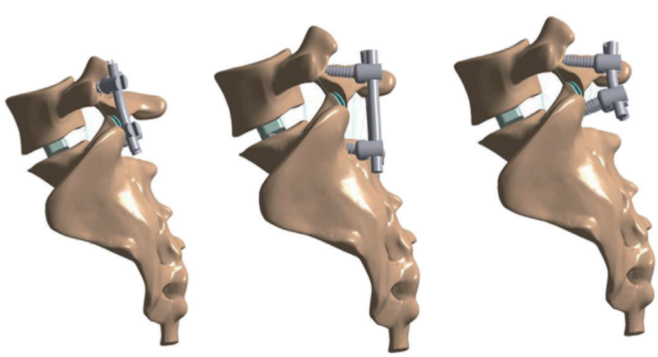

Fig. 1 3D finite element (FE) model of L5–S1 developed by MIMICS software.

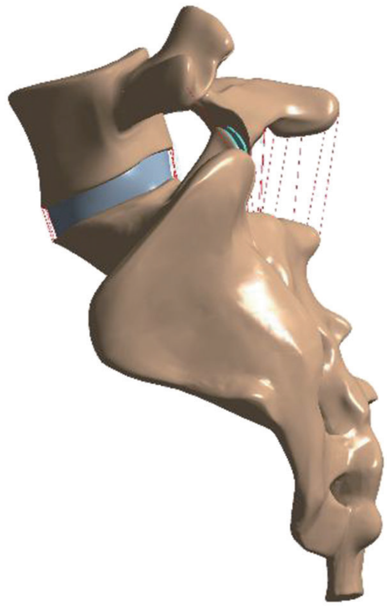

Fig. 2 The models after implantion with cages. The L3–L4 intervertebral disc was excised and implanted with a cage.

The "surface to surface contact," such as the contact between end plates of the vertebra and the intervertebral disc, the contact between the intervertebral disc segments, and the contact between the bone nails and the vertebrae nail, were analyzed using the interaction property "TIE" in the ABAQUS software. The contact between the upper and lower articular process was defined as the finite sliding, with friction coefficient of 0.2.

The nodes of the inferior surface of S1 were fixed in all degrees of freedom.

To compare the differences among the three surgical models under physiological loading conditions, the surgical models were stressed with 400 N of axial compression and 10 Nm moments to simulate extension, flexion, lateral bending, and torsion. The model was also recalculated under the above loading conditions. The range of motion was determined for each loading direction.

Statistical Method

Results are presented as mean ± standard deviation. Data were compared using repeated-measure analysis of variance (ANOVA) and Tukey's significant difference multiple comparison tests. Significance was defined as $P < 0.05$.

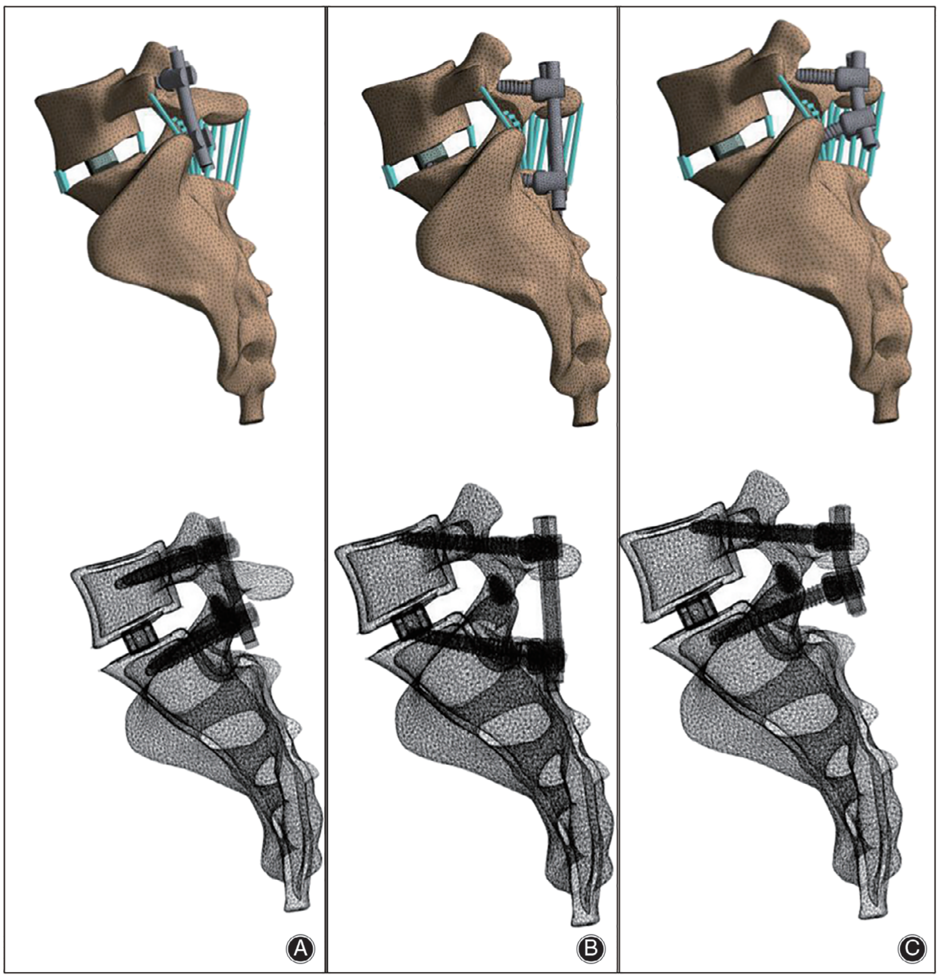

Fig. 3 Traditional pedicle screw (PS) fixation (A, Model A), traditional cortical screw fixation (B, Model B), and new cortical screw fixation (C, Model C) modeled in SOLIDWORKS software.

Results

Model Validation

The FE results for range of motion (ROM) were evaluated to validate our intact model through comparison with other studies under the same loading. The ROM of each segment was defined by the sum of two motion pairs, such as extension and flexion, left and right lateral bending, and left and right torsion. As Fig. 4 shows, the ROM of the present model and previous data reported by Xiao *et al.*[17] were 16.28 and 17.29, 12.43 and 12.56, and 1.98 and 2.70, respectively, for extension and flexion, lateral bending, and torsion. There is no significant difference in ROM between our model and that of Xiao *et al.*[17] ($P > 0.05$), which means that our model is valid for the following test.

Vertebral Displacement

When torsion force concentrates on one vertebra, vertebral displacement occurs because of the movement limitation of the small joint. In this study, we measured the vertebral displacement to evaluate the torsion force of three different types of screw. The results of vertebral displacement show that there is no significant difference in extension and flexion among Models A, B, and C ($P < 0.05$). However, the displacement of left and right torsion in Model C (0.31 and 0.40 mm, respectively) is less than that of Model B (0.41 and 0.58 mm, respectively), with significant difference ($P < 0.05$). There is no significant difference in left (0.76 mm for Model B and 0.74 mm for Model C) and right (0.50 mm for Model B and 0.53 for Model C) lateral bending between Models B and C ($P > 0.05$). The results are presented in Fig. 5.

Stress on Vertebral Body

In general, compared with Model A, the stresses on the vertebral body of the other two surgical models showed a decreasing trend in extension, flexion, bending, and torsion, as shown in Fig. 6. Model C has relatively lower pressure in extension (48.37 MPa in Model B *vs* 38.92 MPa in Model C) and flexion (41.07 MPa in Model B *vs* 32.46 in Model C) than Model B (both $P < 0.05$).

Stress on Cages

The greater stresses on cages may increase the risk of fine motion and mote on cages, which would cause inflammation of the fused segment and have adverse effects on the fusion process. As shown in Fig. 7, the cages of stress on left bending (162.19 and 160.63 MPa), right bending (150.02 and 150.05 MPa), left torsion (158.45 and 146.27 MPa), and right torsion (167.33 and 171.15 MPa) were all much higher in Models B and C compared to Model A (all $P < 0.05$). The stress on cages of Model C (64.32 MPa) in extension is significantly lower than in Model B (178.88 MPa, $P < 0.05$). Therefore, Model C was obviously inferior to Model B in preventing inflammation and adverse effects.

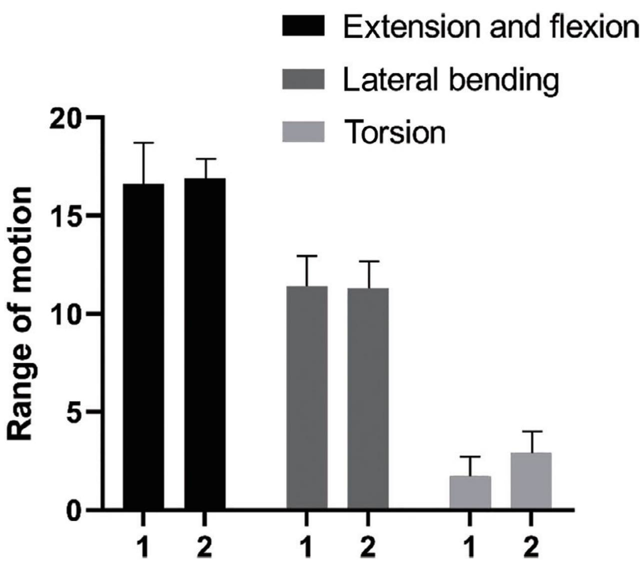

Fig. 4 Comparison of the range of motion (ROM) between our model and the previous study. 1: Our finite element (FE) model. 2: The previous study reported by Xiao *et al.*[17] Results showed no significant difference for ROM between the two results from our study and that of Xiao *et al*.

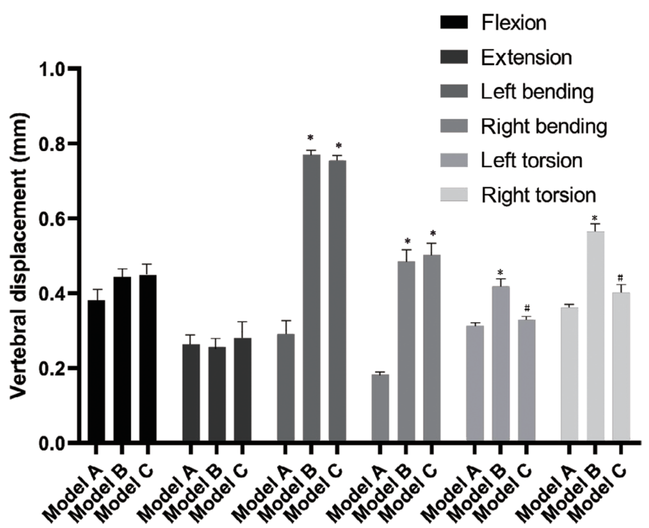

Fig. 5 The results of the vertebral displacement. There was no significant difference in extension and flexion among the three models ($P < 0.05$). However, the displacement of left and right torsion in Model C was significantly less than that of Model B ($P < 0.05$). There was no significant difference in left and right lateral bending between Models B and C ($P > 0.05$), but they were much higher than for Model A ($P < 0.05$). *$P < 0.05$ compared to model A. #$P < 0.05$ compared to model B.

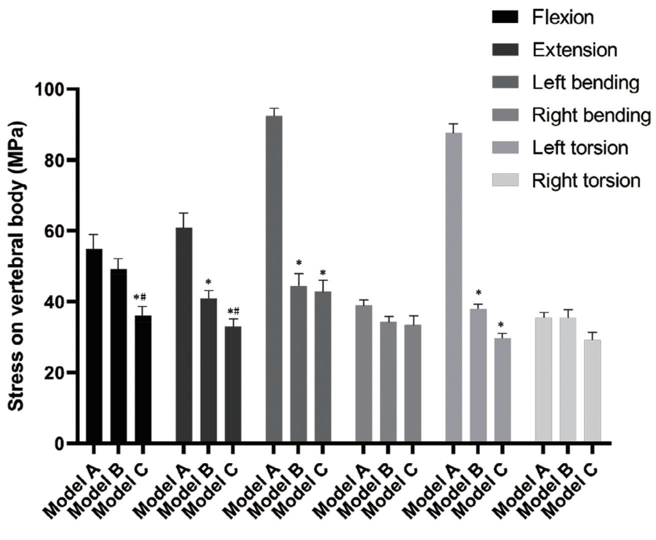

Fig. 6 The average stresses on vertebral body. Compared with Model A, the stresses on the vertebral body of the other two surgical models showed a decreasing trend in extension, flexion, bending, and torsion. Model C has relatively lower pressure in extension and flexion than Model B (both $P < 0.05$). *$P < 0.05$ compared to model A. #$P < 0.05$ compared to model B.

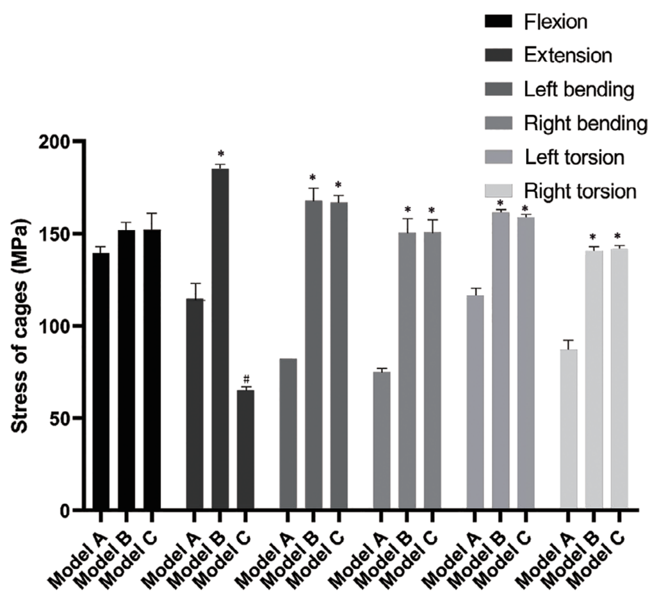

Fig. 7 The average stresses on cages. *$P < 0.05$ compared to model A. #$P < 0.05$ compared to model B. The cages of stress on left bending, right bending, left torsion, and right torsion were all much higher in Models B and C compared to Model A (all $P < 0.05$). The stress on cages of Model C in extension is significantly lower than in Model B.

Stress on Fixation

The stresses on the fixation could be used to predict the fusion rate. As our results show, Models B and C have no significant difference in each loading condition except for left bending and right torsion. In addition, the stresses of Model A in flexion, extension, right torsion, and left and right bending are significantly lower than in the other groups (Fig. 8).

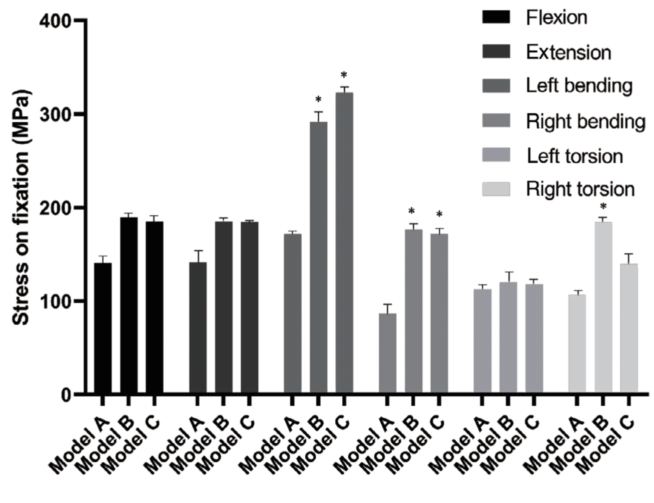

Fig. 8 The results of average stresses on fixation. Models B and C have no significant difference in each loading condition except for left bending and right torsion. Stresses of Model A in flexion, extension, right torsion, and left and right bending are significantly lower than for the other groups. *$P < 0.05$ compared to model A.

Discussion

Insertion Technique of S1 Cortical Screw is Safer than the Pedicle Screw Technique

The traditional PS technique relies on engagement of the trabecular bone within both the pedicle and the vertebral body[18]. In contrast, CBT uses a mediolaterally and caudocranially directed path to go through the pedicle, which increases the contact area of the bone and screw[14]. Compared with the traditional PS technique, the CBT, designed by Santoni *et al.*, takes advantage of a cortically-based track through the pedicle and was proposed to address the weakness seen in PS application[9,19]. According to a meta-analysis, CBT is a better option for patients with osteoporosis and obesity[20]. Another meta-analysis considered that patients who performed CBT had significantly lower postoperative complications than patients treated with PS[21]. Chin *et al.*[22] also proved that CBT is associated with less intraoperative blood loss and shorter length of stay than the traditional PS method. In addition, CBT is superior to PS, with shorter operation time and incision length[23]. Admittedly, there are also potential risks that excessive increase of the diameter of the screw can lead to a pedicle fracture, and the screw being positioned in the wrong direction can cause damage to the superior nerve root. In general, CBT has advantages over the PS method, like lower blood loss and postoperative complications, and shorter operation time and incision length.

Owing to its advantages, CBT has gradually replaced PS and has been advocated as an alternative to standard pedicle screw instrumentation. Despite the increased use of the CBT in spine surgery, little is known about the starting point and insertion technique for the sacral CBT.

The entry point of the traditional insertion technique was the inferolateral corner of the S1 superior articular process and the trajectory aimed anteromedially, parallel to the S1 endplate and into the anterior sacral cortex but not beyond the anterior sacral cortex. Different from the traditional insertion technique, the PES technique allows the distal end of the screw to pass through the upper endplate of the iliac vertebral body, maximizing the contact area between the screw and the cortical bone; the starting point is more inward and the tip of the screw passes through the intervertebral space, making the process of this new technique safer.

Identification of Suitable Starting Points is Necessary for Intervertebral Fusion

In the conventional CBT approach, it is hard to locate starting points in patients who need intervertebral fusion surgery. Once severe lateral slippage occurs, the screw insertion site can become significantly dislocated sideways, which increases the possibility of nerve root damage[24]. Meanwhile, as patients suffering from lumbar foraminal stenosis need to remove a portion of the facet joint to achieve the purpose of releasing, PES technology is no longer applicable. Besides, the anatomical variation of vertebrae in different patients makes it difficult to standardize the starting point. When used in combination with lumbar CBT technology, the insertion point is too far outside the coronal plane, and prebending of the connecting rod is required after the screw is placed. Therefore, when CBT technology is applied in the lumbosacral vertebral section, the insertion point should be more inward than the traditional method of screw placement. In addition, because of the complicated anatomy of the humerus, the fixation of the lumbosacral spine is more difficult. To achieve a strong fixation, the screw must pass through the cortical bone on either side or through the anterior cortex of the tibia to form a three-layer cortical fixation, but this also presents a risk of neurovascular injury.

Advantages of New Insertion Technique for Sacral Cortical Bone Trajectory

With the development of multi-slice spiral CT technology and the application of 3D reconstruction, reconstruction of the spine is accurate. Furthermore, the FE method, as an essential part of biomechanical analysis *in vitro*, has been widely used for the study of spine disease. Therefore, we attempted to use these emerging method to find a new insertion technique for sacral CBT.

In the present study, we evaluated the placement of the traditional S1 pedicle screw, the traditional S1 cortical screw, and the new S1 cortical screw through the FE method. The results demonstrated that the cortical screw exceeds the pedicle screw in stability and pullout force. In addition, the new cortical screw insertion method has almost the same effects as the traditional cortical screw method. However, it demonstrates advantages in promoting the lumbosacral interbody fusion, which protects vessels and nerves. In addition, the screw path of our new insertion technique is away from the nerve roots, which reduces the risk and incidence of postoperative radiculitis and postoperative nerve root injury; thus, the pressure on the spine surgeon is decreased. Moreover, the relatively medial starting point can avoid more soft tissue exposure and further damage of paravertebral muscles, facet joints, and joint capsules.

The limitation of this study is that both the anatomic structures and material properties of ligaments are more simulative and simple than in the actual condition. We did not perform a clinical analysis to explain the clinical effect of this technique in patients.

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