Technology of Cortical Bone Trajectory on the Influence of Stability in Fixation of Burst Fracture of Thoracolumbar Spine: A Finite Element Analysis

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Abstract. Objective: To study the biomechanical stability of a new screw-setting technique, we used cortical bone trajectory (CBT) in injury vertebra relative to the traditional pedicle screw-setting technique.

Methods: We used thoracolumbar spine CT data of a healthy adult male volunteer and engineering data of internal fixation system of spine to simulate intact state, burst fracture state and combination of three kinds of internal fixation state of the spine: (1) 4 pedicle screws cross segment and 2 rods (P4); (2) 4 pedicle screws, 2 CBT screws at injured vertebrae and 2 rods (P4C2); (3) 6 pedicle screws and 2 rods (P6). Then we compared differences of the stability of the corresponding fixed system and stress distribution of fixation models of three groups above.

Results: The total deformation of all nodes of the fracture spine model of P4C2 was less than the fracture spine model node group of P4 and larger than the fracture spine model node group of P6 during normal weight status, rotation (right), bending forward, stretch and lateral bending(right) state. The equivalent stress of all nodes of internal fixation system of P4C2 was smaller than the fixation model node group of P4 and bigger than the fixation model node group of P6 during normal weight status, rotation(right), bending forward, stretch and lateral bending(right) state.

Conclusion: CBT technology for injured vertebra fixation could provide more stability of the vertebral body and reduce stress concentration of internal fixation system compared to the traditional P4 fixation.

Keywords: Burst fracture · Thracolumbar spine · Cortical bone trajectory · Pedicle screw · Biomechanics · Injured level fixation

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1 Introduction

Thoracic lumbar burst fracture is so common that much attention has been paid to the choice of surgical treatment. In spite of the great controversy [1, 2], internal fixation is still a preferred method to cure fractures which have surgical indications. After years of development, traditional pedicle screw-rod system was considered a mature method of treatment for such fractures after repeated testing [3, 4]. The treatment effects were more satisfactory [5, 6]. However, its growth curves were accompanied by the common complications and its limitations [7, 8]. Some accidents in the operation and difficulties for revision surgery also made doctors unprepared. Therefore, it is imperative to develop a safe and effective alternative way for traditional pedicle nailing method in case of need.

Santoni et al. [9] put forward a new kind of pedicle nailing method using cortical bone tunnel, in which the entry points were more inferomedial and the tunnel direction were more cephalad compared to other methods. They concluded that there was no obvious difference between CBT method and the traditional method in the intensity of nailing, and nailing anatomy is the basis of CBT method. Keitaro Matsukawa et al. [10] used the CT images of 100 persons to measure CBT canal of 470 vertebrae by 3D reconstruction software to get CBT channel diameter, length, roll angle of vertebra, and the reverse gantry of vertebral level. They summed up that the pedicle shape and axis angle of pedicle in different lumbar segment were different, but the data of CBT were similar in addition to the diameter. This means that CBT nailing direction and length varies a lot due to vertebral levels. This might reduce incidence of complication. But there are few reports on CBT application in burst fracture of thoracolumbar spine.

Finite element analysis method was applied in this paper to focus on influence of CBT techniques to postoperative vertebral stability of fixed lumbar spine and load distribution of internal fixation, so as to provide objective and theoretical basis for the application of CBT techniques.

2 Materials and Methods

We selected 192 slices raw data (Dicom format) of CT scan (64 spiral computed tomography scanner, Philips, Holland), scan slice 0.6 mm. The thoracolumbar spine was from a 32-year-old healthy male volunteer (height: 173 cm, weight: 75 kg), without history of spinal trauma, malformation or low back pain. The CT data was input into Mimics14.11 (Materialise, Belgium). STL format files of cortical bone, cancellous bone, annulus fibrosus and nucleus pulposus of thoracic lumbar segment (T12-L2) were obtained respectively through threshold segmentation, dynamic regional growth, cavity filling and Boolean operation steps with the help of the image segmentation tools. Then these files were input into Geomagic Studio12 (Geomagic, USA), after hole filling and deburring treatment, they were re-imported into Mimics. Then we got volume meshes, and cdb files of these parts directly from the corresponding mask (Hexahedral 8-point type). Then the cdb files were put into ANSYS Workbench 14.5 (Ansys, USA), assembled in the FE model module, and connected to the Static Structural module, where physical properties, elasticity modulus, contact condition of corresponding parts were defined. After ligament simulation, we determined thrust surface and fixed surface, set test stress and torque with directions, and planned the action time and the step length. Under mechanical condition and environment similar to classical biomechanical experiments in vitro, we finished the validation of the intact thoracic lumbar spine model.

The data of L1 vertebral body was input singly to Mimics, which was changed into fracture model with the use of the cutting function (Fig. 1). Then we got the corresponding vertebral fracture (cortical and cancellous bone) cdb files (Hexahedral 8-point type) just like the above steps, which were applied in the thoracic lumbar burst fracture model.

Fig. 1. Intact thoracic lumbar spine model and fractured model

Pedicle screw system and CBT screw system (Shangdong Weigao Biotech Co. Ltd) consisted of six pedicle screws (5.5 mm in diameter, 50 mm in length), two CBT screws (4.0 mm in diameter, 40 mm in length) and two connecting roots (6.0 mm in diameter, 100 mm in length). The simulation was completed by Solidworks 2012 software. After the formation of their stl files, we used Mimics to get their cdb documents directly from the mask body grid (Hexahedral 8-point type).

Surgery simulation system was contributed to the assembling of pedicle screw or CBT screw internal fixation system on fracture model. Traditional pedicle screw fixation and injured vertebral insertion models were made respectively: (1) 4 pedicle screws cross segment and 2 rods (P4); (2) 4 pedicle screws, 2 CBT screws at injured vertebrae and 2 rods (P4C2); (3) 6 pedicle screws and 2 rods (P6) (Fig. 2). We simulated normal weight status (NW), bending forward (BF), stretch (ST), rotation right (RR) and lateral bending right state (BR) respectively, and then calculated. Recorded results of the corresponding fixed system were compared in the total deformation of all nodes of the fracture spine model and the stress distribution of all nodes of fixation models of three groups above. The material properties are shown in table [11] (Table 1).

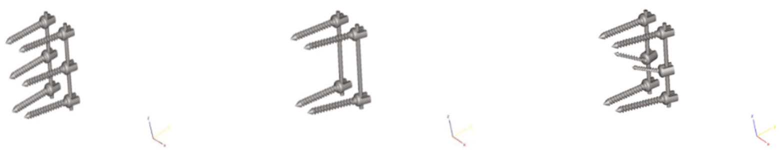

Fig. 2. Simulation of traditional pedicle screw fixation (P4, P6) and P4C2

Table 1. Material properties of human thoracolumbar spine

Materials	Young's modulus(MPa)	Poisson's ratio
Cortical bone	12000	0.3
Cancellous bone	100	0.2
Nucleus pulposus	1	0.49
Anulus fiber	400	0.3
Cortical bone (fractured)	1000	0.3
Cancellous bone (fractured)	10	0.3
Screw fixation	110000	0.3

Additional attachment included the interspinous ligament, supraspinous ligament, intertransverse ligament, anterior longitudinal ligament, posterior longitudinal ligament was simulated as incompressible spring element (Fig. 3), with axial stiffness (longitudinal stiffness) of 70000 N/m and axial damping (longitudinal damping) is 7000 N • s/m [12].

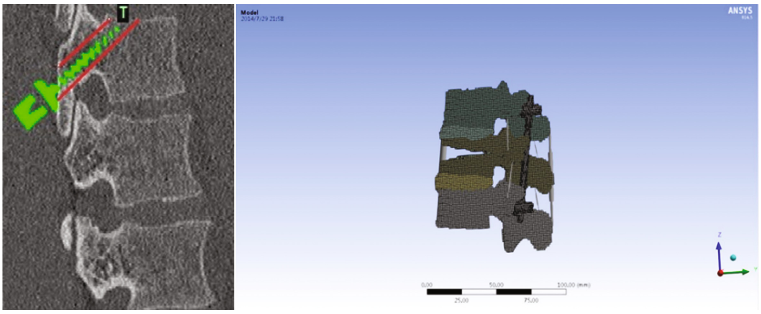

Fig. 3. The bone tunel of CBT screw and the internal fixation model with ligaments

3 Results

After the pre-treatment of finite element, contact mode of T12-L2 was obtained, the L1 burst fracture model and internal fixation model were also built based on it (Fig. 3). We got 133296 nodes (fractured spine model), 30365 nodes (P4), 39564 nodes (P4C2), 42282 nodes (P6) totally.

3.1 Model Validation

We compared ROM (range of angular movement) of virtual model in the study with classic biomechanical study in vitro of thoracolumbar segment specimen to validate the model (Fig. 4). After comparison, the finite element model of our study performanced similar to the specimen model in vitro biomechanical study of Markolf [13] in angular displacement - the applied torque gradient curve, results shown in figure. As a result, this finite element model had high reliability and it could be used in the biological mechanics simulation study effectively.

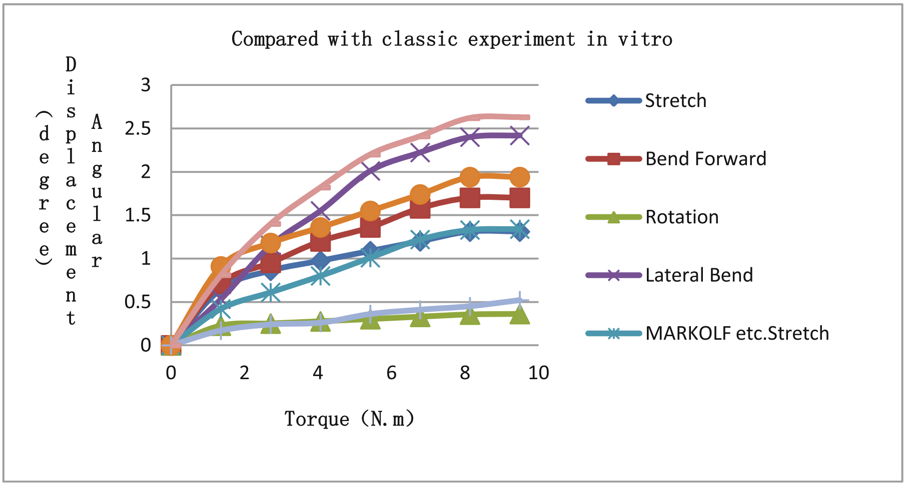

Fig. 4. The validation of the model

Mechanics Analysis

A. Total Deformation

The results of total deformation of five models were calculated out from Workbench static structural analysis system according to the previous steps: NW, BF, ST, RR, BR, and they were exported in excel format, which were the total deformation data of all nodes of the fracture model. The data of total deformation of all nodes in three kinds fixed fracture models was chosen. And then five kinds of model including intact model, burst fracture model, and three kinds of different internal fixation model were imported into statistics software SPSS 19. The mean and standard deviation were calculated, and went through paired sample T test. P values were obtained (Table 2).

Table 2. Total deformation of vertebrae nodes (mm, $\bar{X} \pm S$)

Group / State	* Intact	**Fractured	P4	P4C2	P6
NW	0.037±0.036	0.239±0.273	0.058±0.044	0.046±0.037	0.040±0.035
BF	0.048±0.041	0.588±0.690	0.143±0.133	0.126±0.116	0.102±0.097
ST	0.157±0.096	0.293±0.209	0.152±0.090	0.124±0.076	0.090±0.059
RR	0.081±0.052	0.447±0.513	0.090±0.068	0.075±0.058	0.069±0.053
BR	0.103±0.070	0.287±0.275	0.121±0.086	0.092±0.076	0.073±0.065

By statistical comparison, we found average total deformation of fracture model were greater than the complete model in each movement and its standard deviation. And average total deformation and its standard deviation of fracture model were significantly decreased after using three kinds of internal fixation; The total deformation of all nodes of the fracture spine model of P4C2 during normal weight status, and rotation (right), bending forward, stretch, lateral bending (right) state, was less than the fracture spine model node group of P4, and larger than the fracture spine model node group of P6.

B. Equivalent Stress (von Mises)

Three kinds of internal fixation model were calculated in the workbench Static Structural analysis system to get the results according to the previous steps (Figs. 5, 6 and 7). Data of equivalent stress was exported in excel format. We selected the data of all nodes in fixation models for observation. Three sets of data of internal fixation models in the equivalent stress were imported into statistics software SPSS 19 in sequence according to five kinds of state: state of NW, BF, ST, RR, BR. The mean and standard deviation were calculated, and P values were obtained through the single factor analysis of variance (ANOVA) (Table 3).

Table 3. Equivalent stress of nodes of internal fixation (MPa, $\bar{X} \pm S$)

Group / State	* P4	P4C2	P6
NW	5.850 ± 7.829	3.947 ± 5.736	3.096 ± 4.367
BF	13.045 ± 15.877	8.222 ± 10.609	11.260 ± 16.359
ST	6.709 ± 11.734	4.268 ± 7.498	3.744 ± 6.530
RR	8.344 ± 10.716	5.553 ± 7.889	4.539 ± 6.200
BR	6.854 ± 10.547	5.499 ± 7.101	4.149 ± 6.374

* Control group: P4 Experimental group: P4C2 and P6 $P < 0.001$

The equivalent stress of all nodes of internal fixation system of P4C2 during normal weight status, rotation (right), bending forward, stretch and lateral bending (right) state was smaller than that of P4, but bigger than that of P6 (except BF state).

We took BF state for example to explain the difference of equivalent stress in the three fixed models. In P4C2 model, the stress was more smoothly distributed in the screw-rod fixation than the P4 and P6 model (Figs. 5, 6 and 7). The data was compared by SNK test and we found it had obvious differences between three models (Table 4).

Table 4. The data of three models in bend forward state under Student-Newman-Keuls (SNK) test

Group	N	Alpha = 0.05		
		1	2	3
P4C2	39,564	8.22225798		
P6	42,282		11.26014106	
P4	30,365			13.04458581
Significance		1.000	1.000	1.000

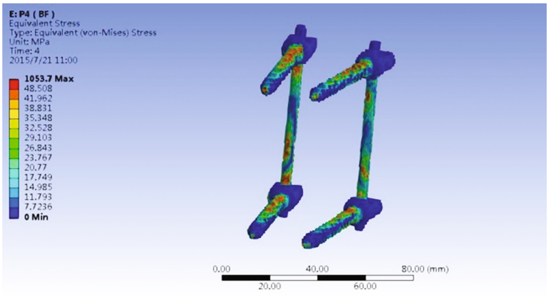

Fig. 5. Equivalent Stress of P4 model in BF state

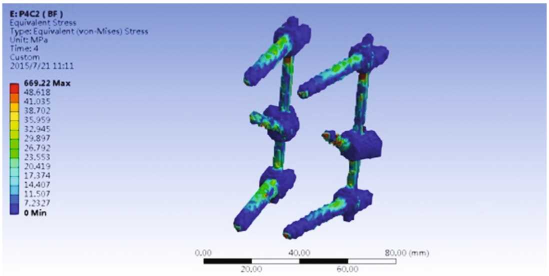

Fig. 6. Equivalent Stress of P4C2 model in BF state

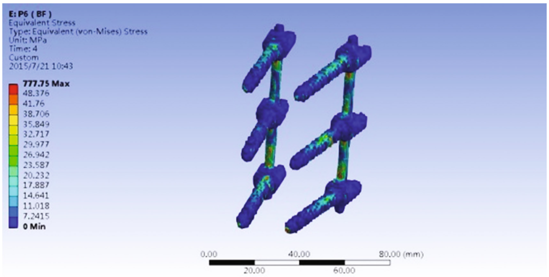

Fig. 7. Equivalent Stress of P6 model in BF state

4 Discussion

Traumatic fractures in thoracic lumbar segment (T10–L2) were the most common, and burst fractures in thoracic lumbar segment were representative of high energy damage which accounted for about 10% to 20% [14]. It is controversial for internal fixation of spinal fracture of osteoporosis, and the mainstream of research about it turns to the specialty of pullout resistance and anti-loosening of internal fixation. Solid mechanics experiment has been golden standard for comparing fixation or fusion treatment methods. Luis Perez-Orribo [15] considered that bilateral CBT nailing method provided similar stability to bilateral pedicle screw system in the specimen, regardless of intervertebral fusion. The CBT method could theoretically reduce the damage when compared with the traditional method.

It is a kind of simulation experiments for finite element analysis, and the reliability of the experimental results depends on the accuracy of model simulation. We had compared with the traditional classical experiments in vitro, and the finite element model seems to act the same as the classic experiments of mechanics, and the movement state had played similar angular displacement curve. So we believed the reliability of the model,and its well application to simulate the target segment of spinal and play similar biomechanics characteristics. After all, the finite element model is a kind of virtualization of the real state and a product of the development of computer technology. So we need further research to prove whether it can lead a right direction to represent real human spine and show believable results.

Single axial stress was equivalent to the multiple axis stress, and we make a uniaxial tensile force equivalent to six components of stress to the deformable body. The equivalent stress explores difference of stress on materials in all directions, and is mainly used to describe the phenomenon of stress concentration. In this paper, the result can reflect difference in equivalent stress of material of the three internal fixation model in the fracture model under stress. Objectively it could give expression to concentration degree of stress in internal fixation model, and indirectly reflect their difference in ability of load dispersion. Thus it could provide the reference to evaluate the stability and the service life of the fixation. This research cited the classic literature and used its material assignment only, but could not show all the properties of materials, such as yield, plastic deformation properties. So there was a certain gap from the real situation, and we will take into account in future.

The anterior column was not affected by the method of CBT. The diameter of the cortical bone tunnel was less and the length was shorter than that of the pedicle screws, so the compression of the cortical bone were smaller than that of the pedicle screws. Bone cutting can be also reduced compared with the pedicle screw method because of smaller screws and more content of cortical bone. CBT screws can also be inserted into vertebral bodies where the pedicle screws are already existed; thus, the CBT method is valuable in repeat surgery of same vertebrae.

Mechanics research based on fresh specimens is an ideal method of spinal biomechanics research. We used pre-processing and finite element analysis software to simulate the biomechanical state of spine, and calculate the corresponding results. Four kinds of simple motion state were tested in this study, and we should research more complex integrated motion, such as composite movement and its corresponding composite stress state. We will deepen the research and make the model perfect to obtain more accurate results.

5 Conclusion

CBT technology for injured vertebra fixation could provide more stability of the vertebral body and reduce stress concentration of internal fixation system when compared to the traditional P4 fixation. But it was still inferior to the P6 method in the two aspects.

Conflict of Interest
The authors declare that they have no conflict of interest.

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References

1. Woodall Jr., J.W.: Evidence for the treatment of thoracolumbar burst fractures. Curr. Orthop. Pract. **23**(3), 188–192 (2012)
2. Canbek, U., Karapinar, L.: Posterior fixation of thoracolumbar burst fractures: Is it possible to protect one segment in the lumbar region? Eur. J. Orthop. Surg. Traumatol. **24**(4), 459–465 (2014)
3. Gaines Jr., R.W.: The use of pedicle-screw internal fixation for the operative treatment of spinal disorders. Bone Joint Surg. **82-A**(10), 1458–1476 (2000)
4. Ruf, M., Harms, J.: Pedicle screws in 1-and 2-year-old children: technique, complications, and effect on further growth. Spine **27**(21), 460–466 (2002)
5. McCormack, T., Karaikovic, E., Gaines, R.W.: The load-sharing classification of spine fractures. Spine **19**(15), 1741–1744 (1994)
6. Gelb, D., Ludwig, S.: Successful treatment of thoracolumbar fractures with short-segment pedicle instrumentation. J Spinal Disord. Tech. **23**, 293–301 (2010)
7. Esses, S.I., Sachs, B.L., Dreyzin, V.: Complications associated with the technique of pedicle screw fixation. A selected survey of ABS members. Spine **18**(15), 2231–2238 (1993)
8. Saita, K., Hoshino, Y., Kikkawa, I., et al.: Postlerior spinal shortening for paraplegia after vertebral collapse cause by osteopomsi. Spine **25**(21), 2832–2835 (2000)
9. Santoni, B.G., Hynes, R.A., McGilvray, K.C., et al.: Cortical bone trajectory for lumbar pedicle screws. Spine J. **9**, 366–373 (2009)
10. Matsukawa, K., Yato, Y.: Morphometric measurement of cortical bone trajectory for lumbar pedicle screw insertion using computed tomography. J. Spinal Disord. Tech. **26**(6), 248–253 (2013)
11. Shih, S.-L., Chen, C.-S., Lin, H.-M., et al.: Effect of spacer diameter of the dynesys dynamic stabilization system on the biomechanics of the lumbar spine: a finite element analysis. J. Spinal Disord. Tech. **25**(5), 140–149 (2012)
12. Ozgur, V., Mehmet, S.E., Levent, A., et al.: Biomechanical Evaluation of Syndesmotic Screw Position: a finite element analysis. J. Orthop. Trauma **28**(4), 210–215 (2014)
13. Markolf, K.L.: Deformation of the thoracolumbar intervertebral joints in response to external load: a biomechanical study using autopsy material. J. Bone Join Surg. Am. **54**(3), 511–533 (1972)
14. Wood, K.B., Li, W.: Management of thoracolumbar spine fractures. Spine J. **14**, 145–164 (2014)
15. Perez-Orribo, L., Kalb, S., et al.: Biomechanics of lumbar cortical screw-rod fixation versus pedicle screw-rod fixation with and without interbody support. Spine **38**(8), 635–641 (2013)