Int J Clin Exp Med 2017;10(11):15329-15334
www.ijcem.com /ISSN:1940-5901/IJCEM0052973

Original Article

A finite element analysis for biomechanics of screw placing methods at fracture level of lumber vertebrae by using injured vertebral pedicel screws internal fixation

Lei Tan[1*], Yan-Hui Li[2*], Jian Wang[3], Bin Zhao[4], Chao Liu[1], Dong Zhu[1]

Departments of [1]Orthopedic Trauma, [2]Cardiology, [3]Burn, The First Hospital of Jilin University, Changchun, Jilin 130021, China; [4]Department of Orthopedic, Binzhou People's Hospital, Binzhou, Shandong 256600, China. [*]Equal contributors.

Received July 20, 2016; Accepted June 28, 2017; Epub November 15, 2017; Published November 30, 2017

Abstract: This study aims to investigate and analyze biomechanics of lumber vertebra and vertebral pedicel screws, and explored effects of different screw placement on lumber vertebral stability and distribution of fixation stress. The normal lumber vertebrae 1 (L1) to lumber vertebrae (L5) three-dimensional finite element model was established firstly. Different screw placement of injured vertebral pedicel screws internal fixation for lumber vertebra fracture three-dimensional finite element analysis model were also established secondarily. The fracture three-dimensional model was divided into Control group (NC group), placing long-screws into injured vertebral plate horizontally (LH group), placing short-screws into injured vertebral plate horizontally (SH group), placing long-screws into injured vertebral plate obliquely (LO group), and placing short-screws into injured vertebral plate obliquely (SO group). The axial displacement, bending angle, compressive stress were observed in L3 lumber vertebrae. Results of ante-flexion, backward-extension, lateral bending, rotation in fracture model were successfully established. The results indicated that axial displacement and bending angle in IVPSIF treated fracture model groups were significantly smaller in range compared to normal lumber vertebral mode. Compressive stress in oblique screws (SO group and LO group) were significantly decreased compared to horizontal screws (LH group and SH group) ($P<0.05$) for ante-flexion and backward-extension loading. L3 lumber vertebrae compressive stress in oblique screws (SO group and LO group) were significantly decreased compared to horizontal screws (LH group and SH group) ($P<0.05$) for ante-flexion and backward-extension loading. In conclusion, this three-dimensional finite element analysis study found that oblique downward fixation method could scatter compressive stress when treating lumber vertebral fracture, and further prevent internal fixation breaking and pedicle screws loosing.

Keywords: Lumber vertebra fracture, placing screw at injured vertebrae, biomechanics, finite element analysis

Introduction

Lumber vertebra fracture is the most common type of fracture. In clinical, the posterior short segment pedicle screw fixation is the classical method for the lumber vertebra fracture therapy. However, due to the diligence for the injured vertebrae treatment, the final internal fixation rate even achieves 20% [1, 2] in clinical. Shen *et al.* [3] firstly reported the pedicel screws internal fixation for injured vertebral, which provides partial kyphosis correction and relieves the earlier pain. The following studies [4, 5] also further developed this method and obtained the satisfied clinical outcomes, such as the better restoration of fracture, the stability of injured vertebrae. Through the above studies mainly compared the outcomes of the traditional and classical posterior short segment pedicle screw fixation with the injured vertebral pedicel screws internal fixation (IVPSIF method), the screw placements are rarely investigated and the controversial methods are extensively exist in clinical [6, 7].

This study established the different injured vertebral pedicel screws placement methods in the lumber vertebra fracture three-dimensional finite element analysis model, and mimicked the motion of vertebrae, the ante-flexion, ante-extension, backward-flexion, backward-extension and axial rotation of lumber vertebra. This study mainly analyzed the biomechanics of the lumber vertebra and vertebral pedicel screws, and explored the effects of different screw placement on the lumber vertebral stability and the distribution of fixation stress.

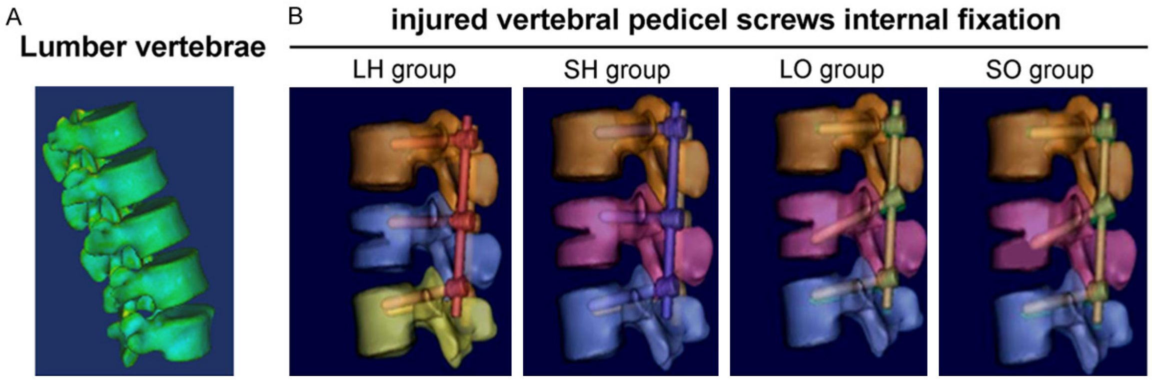

Figure 1. Image of normal three-dimensional and three-dimensional finite element analysis model of different screw placement of injured vertebral pedicel screws. A. Three-dimensional image for L1 to L5 lumber vertebrae and the intervertebral disk. B. Three-dimensional finite element analysis model of different screw placement of injured vertebral pedicel screws internal fixation for the lumber vertebra fracture.

Materials and methods

Data collection

In this study, the health individuals without vertebral disease history were involved and scanned by using the CT. All of the individuals have given their consents and approved this study. This study was also approved by the ethics committee of The First Hospital of Jilin University, Changchun, China.

Modeling for normal lumber vertebrae

The scanned CT data were stored as the Dicom format and then imputed into the Mimics software to establish three-dimensional model for L1 to L5 lumber vertebrae and the intervertebral disk (with the material characteristics) (**Figure 1A**).

Secondarily, fixing the L5 lower vertebral plate and then forcing the L1 upper vertebral plate with 500 N vertical compressive load. Then, the ante-flexion, ante-extension, latero-flexion, latero-extension compressive load were also forced with 10 N, respectively. Finally, the average stiffness (Nm) was calculated and compared with the documented literatures to evaluate the effectiveness of the model.

Different screw placement of injured vertebral pedicel screws internal fixation for lumber vertebra fracture three-dimensional finite element analysis model

After the establishment of normal lumber vertebrae model, the lumber vertebral fracture model was established by cutting (V shape) and drilling the lumber vertebrae. The established fracture model was given the material characteristics and assembled with the pedicle screw model in the Abaqus software. Finally, the following 5 groups were established: Control group (NC group) was assigned as the normal control group; LH group was assigned by placing the long-screws into the injured vertebral plate horizontally (6×40 mm); SH group was assigned by placing the short-screws into the injured vertebral plate horizontally (6×35 mm); LO group was assigned by placing the long-screws into the injured vertebral plate obliquely (6×40 mm); SO group was assigned by placing the short-screws into the injured vertebral plate obliquely (6×35 mm) (**Figure 1B**).

Model controlling and compressive stress forcing

According to the body bearing ability, the compressive stress loading was performed for every group. For the lumber vertebrae anteflexion and latero-extension, 150 N stress was forced firstly, consequently 6 Nm blending stress was forced. For the lumber vertebrae lateral bending, 200 N stress was forced firstly, consequently 8 Nm blending stress was forced.

Observation index

The axial displacement, bending angle, compressive stress were observed in the L3 lumber vertebrae.

Statistical analysis

All statistical analyses were performed using SPSS 21.0 (SPSS Inc., Chicago, IL, USA). The differences in axial displacement, bending angle, compressive stress among the groups was compared by using the ANOVE following with the post-hoc test in this study. Data were showed as the mean ± SD, and significant difference was remarked with a *P* value less than 0.05.

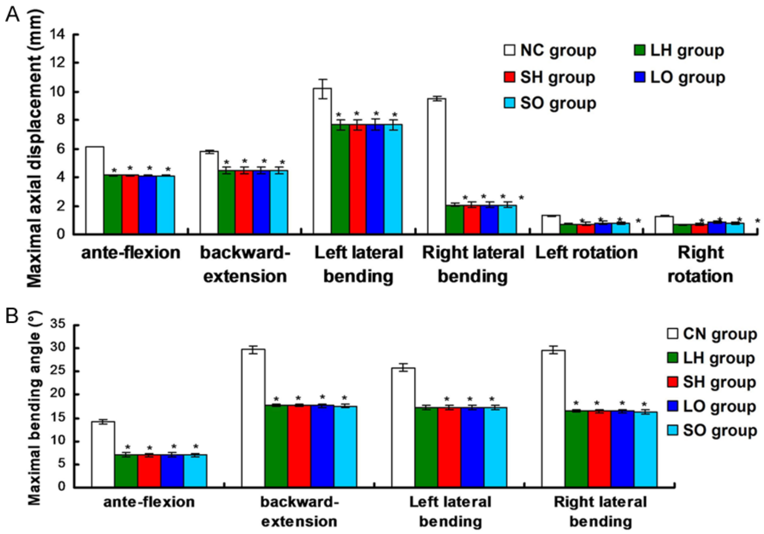

Figure 2. The maximal axial displacement and bending angle in every finite element analysis model group. A. Maximal axial displacement for ante-flexion, backward-extension, left lateral bending, right lateral bending, left rotation and right rotation in different group. B. Maximal bending angle for ante-flexion, backward-extension, left lateral bending and right lateral bending in different group. *P<0.05 represents the maximal axial displacement or bending angle in LH group or SH group or LO group or SO group compared to the NC group. NC: control group; LH group: placing the long-screws into the injured vertebral plate horizontally (6×40 mm); SH group: placing the short-screws into the injured vertebral plate horizonally (6×35 mm); LO group: placing the long-screws into the injured vertebral plate obliquely (6×40 mm); SO group: placing the short-screws into the injured vertebral plate obliquely (6×35 mm).

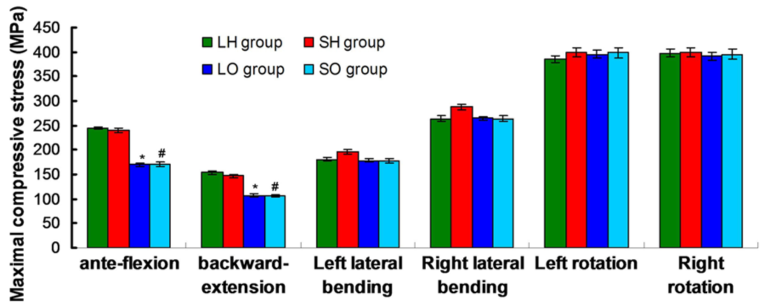

Figure 3. The maximal compressive stress in every finite element analysis model group. *P<0.05 represents the maximal compressive stress in LO group compared to LH group, or maximal compressive stress in SO group compared to SH group. LH group: placing the long-screws into the injured vertebral plate horizontally (6×40 mm); SH group: placing the short-screws into the injured vertebral plate horizontally (6×35 mm); LO group: placing the long-screws into the injured vertebral plate obliquely (6×40 mm); SO group: placing the short-screws into the injured vertebral plate obliquely (6×35 mm).

Results

Identification for the model effectiveness

We firstly forced the compressive load to the established lumber vertebrae model, compared the data with the data documented in the previous studies. The results indicated the ante-flexion, backward-extension, lateral bending, rotation in present study (1.61, 3.14, 2.41 and 5.02, respectively) was within the range of Yamamoto *et al.*'s report (1.75, 3.22, 2.41 and 5.26, respectively) [8] and Heth *et al.*'s report (1.1, 2.35, 1.33 and 2.61, respectively) [9]. Therefore, we confirmed that the established lumber vertebral model is effectiveness.

No differences for axial displacement and bending angle among group

The results indicated that the axial displacement (**Figure 2A**) and the bending angle (**Figure 2B**) in IVPSIF treated fracture model groups were significantly smaller in range compared to the normal lumber vertebral model (**Figure 2**, P<0.05). However, there were not significant differences among all of the four treated groups (**Figure 2**, P>0.05).

Oblique screws decreases compressive stress compared to horizontal screws

According the **Figure 3**, we found that the compressive stress in oblique screws (SO group and LO group) were significantly decreased compared to the horizontal screws (LH group

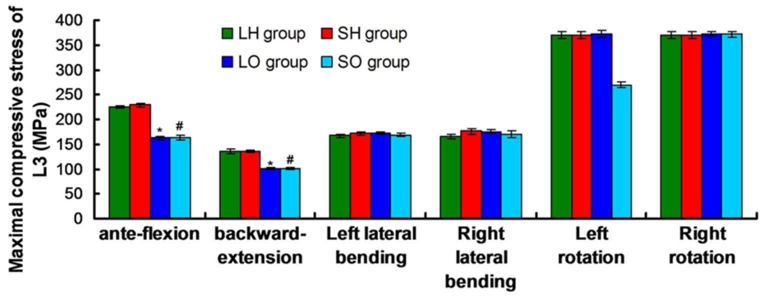

Figure 4. The maximal compressive stress in L3 lumber vertebrae in every finite element analysis model group. *P<0.05 represents the maximal compressive stress in L3 lumber vertebrae in LO group compared to LH group, or maximal compressive stress in SO group compared to SH group. LH group: placing the long-screws into the injured vertebral plate horizontally (6×40 mm); SH group: placing the short-screws into the injured vertebral plate horizonally (6×35 mm); LO group: placing the long-screws into the injured vertebral plate obliquely (6×40 mm); SO group: placing the short-screws into the injured vertebral plate obliquely (6×35 mm).

and SH group) (P<0.05) for the ante-flexion and backward-extension loading. However, there were not significant differences among the four groups for the other loadings.

Oblique screws decreases compressive stress of L3 lumber vertebrae

Due to the importance of the L3 lumber vertebrae, we examined the compressive stress of L3 lumber vertebrae. The results indicated that the L3 lumber vertebrae compressive stress in oblique screws (SO group and LO group) were significantly decreased compared to the horizontal screws (LH group and SH group) (**Figure 4**, P<0.05) for the ante-flexion and backward-extension loading. However, there were not significant differences for the L3 lumber vertebrae among the four groups for the other loadings.

Discussion

The posterior short segment pedicle screw fixation (always named 4 screws fixation system) [10] is the traditional and classical therapeutic method for the lumber vertebrae injury or fracture, which characterizes as simple processes, ideal resent, small side-injury, convenient treatment for the attached injured tissues. However, the injured vertebral pedicel screws internal fixation (named as 6 screws fixation system in this study) [11, 12] is a novel fixation method, and more and more reports and application of this method were reported in the recent years. The previous studies have discovered many merits for the injured vertebral pedicel screws internal fixation [13, 14]: ① Increasing the amounts of screws and scattering the connection stress; ② Fixing the fractures directly and providing the propulsive force; ③ Recovering the continuity of the anterior-screw, middle-screw and hinder-screw, increasing the self-stability of injured vertebrae; ④ Decreasing the parallelogram effect. Many biomechanical studies [14-16] proved that the injured vertebral pedicel screws internal fixation is more stable compared to the traditional method, which could reduce the loosing of reset, decrease the possibility of injured vertebrae re-damage, and better than the classical 4 screws fixation. Therefore, this study did not repeat the former experiments, and not assigned the 4 screws control group.

For the implanting depth of the pedicle screw, many different studies have been reported in the recent years. Roy-Camille *et al.* [17] implanted the pedicle screws into 50% to 60% channel length of the lumbar vertebrae. Feng *et al.* [18] implanted the pedicle screws into 80% channel length of the lumbar vertebrae. However, Krag *et al.* [19] found that the resistant capability for the loading strength implanting 80% channel length is higher significantly compared to the implanting 50% channel length. Therefore, in this study, we implanted the pedicle screws into 80% channel length of the lumbar vertebrae, and obtained satisfied outcome.

Weinstein *et al.* [20] reported that when the length of the pedicle screw of the injured vertebral pedicel screws internal fixation achieves to the depth of 1/3 lumber body, and the pedicle screw could provide enough fixed force to the lumber body. Moreover, this kind of internal fixation could either attain the goal of reset, fixation and correction of deformity, or attain the goal of avoiding remove of fracture segments. The pedicle screw used in this study was also designed as Weinstein *et al.*'s report. This study discovered that there were no significant differences for the ante-flexion, backward-extension, left lateral bending, right lateral bending, left rotation and right rotation between the same directed pedicle screws with different length. This suggests that when the pedicel screws internal fixation achieves the depth of 1/3 lumber body, there were no effects of the injured pedicle screw on the lumbar vertebrae stability and screws themselves by force. The role of injured vertebral pedicel screws internal fixation mainly works on the vertebral pedicle, and the out-scope region of pedicle screws is the fracture region, which can't increase the stability of the injured lumbar vertebrae. Contrary, the length pedicle screw is more dangerous, which could fix the fracture segments at the worse location.

Theoretically, the pedicle screw implanting mainly includes three methods, such as horizontal implanting, oblique upward implanting and oblique downward implanting. All of the three methods could be performed in the normal lumbar body implantation. However, it's different in the injured lumbar vertebrae. The injured lumbar vertebrae mainly characterizes as upper edge compression, the oblique upward implanting method is prone to fix the fracture segments in the worse location. Therefore, this study has not selected the oblique upward implanting method. Our results showed that for the same length with different implanting directed screws, there were not significant differences for the loading lower-shift and the bending angles ($P>0.05$). However, the compressive stress in oblique screws (SO group and LO group) were significantly decreased compared the horizontal screws (LH group and SH group) ($P<0.05$) for the ante-flexion and backward-extension loading. These results suggest that the injured vertebral pedicel screws (oblique screws) internal fixation method could share the loads more uniformly, and avoid the intensive compressive stress. Therefore, the oblique screws method could prevent internal fixation breaking and pedicle screws loosing more effectively.

In summary, the three-dimensional finite element analysis study found that the oblique downward fixation method could scatter the compressive stress when treating the lumber vertebral fracture, and further prevent the internal fixation breaking and pedicle screws loosing.

Acknowledgements

This study was granted by the National Natural Science Found (Grant Nos. 11602093, 1127-2134 and 11432016).

Disclosure of conflict of interest

None.

Address correspondence to: Dr. Dong Zhu, Department of Orthopedic Trauma, The First Hospital of Jilin University, No. 71 Xinmin Street, Changchun 130021, Jilin, China. Tel: +86-0430-81875761; E-mail: xiaogliu@yeah.net

References

[1] Wang L, Li J, Wang H, Yang Q, Lv D, Zhang W, Tang K, Shang L, Jiang C, Wu C, Ma K, Wang B, Liu Y, Zhang R, Shang X, Kou D, Jia X, Yang X, Tang Y, Zhang M, Wang P, Xu Y, Wang S. Posterior short segment pedicle screw fixation and TLIF for the treatment of unstable thoracolumbar/lumbar fracure. BMC Musculoskelet Disord 2014; 15: 40.

[2] Kuklo TR, Polly DW, Owens BD, Zeidman SM, Chang AS, Klemme WR. Measurement of thoracic and lumbar fracture kyphosis: evaluation of intraobserver, interobserver, and technique variability. Spine 2001; 26: 61-65.

[3] Shen WJ, Liu TJ, Shen YS. Nonoperative treatment versus posterior fixation for thoracolumbar junction burst fracrues without neurologic deficit. Spine 2001; 26: 1038-1045.

[4] Baaj AA, Reyes PM, Yagoobi AS, Uribe JS, Vale FL, Theodore N, Sonntag VK, Crawford NR. Biomechanical advantage of the index-level pedicle screw in unstable thoracolumbar junction fractures. J Neurosurg Spine 2011; 14: 192-197.

[5] Theologis AA, Tabaraee E, Toogood P, Kennedy A, Birk H, McCelellan RT, Pekmezci M. Anterior corpectomy via the mini-open, extreme lateral, transpsoas approach combined with short-segment posterior fixation for single-level traumatic lumbar burst fractures: analysis of health-related quality of life outcomes and patient satisfaction. J Neurosurg Spine 2016; 24: 60-68.

[6] Yan S, Su F, Zhang ZM. Biomechanical study of the influence of staility of the predicle screws fixation by injured vertebral screw when the pedicle cortex perforation. Zhongguo Yi Xue Yuan Xue Bao 2014; 36: 415-419.

[7] Khan I, Nadeem M, Rabbani ZH. Thoracolumbar junction injuries and their management with pedicel screws. J Ayub Med Coll Abbottabad 2007; 19: 7-10.

[8] Yamamoto I, Panjanbi MM, Crisco T, Oxland T. Three-dimensional movements of the whole lumbar spine and lumbosacral joint. Spine 1989; 14: 1256-1260.
[9] Heth JA, Hitchon PW, Goel VK, Rogge TN, Drake JS, Torner JC. A biomechanical comparison between anterior and transverse interbody function cages. Spine 2001; 26: E261-267.
[10] Li C, Zhou Y, Wang H, Liu J, Xiang L. Treatment of unstable thoracolumbar fractures through short segment pedicle screw fixation techniques using pedicle fixation at the level of the fracture: a finite element analysis. PLoS One 2014; 9: e99156.
[11] Yan S, Su F, Zhang ZM. Biomechanical study of the influence of stability for the pedicle screws fixation by injured vertebral screw when the pedicel cortex perforation. Zhongguo Yi Xue Ke Xue Yuan Xue Bao 2014; 36: 415-419.
[12] Yin F, Sun Z, Yin Q, Liu J, Gu S, Zhang S. A comparative study on treatment of thoracolumbar fracture with injured vertebra pedicle instrumentation and cross segment pedicle instrumentation. Zhongguo Xiu Fu Chong Jian Wei Ke Za Zhi 2014; 28: 227-232.
[13] Li QL, Li XZ, Liu Y, Zhang HS, Shang P, Chu ZM, Chen JC, Chen M, Qin R. Treatment of horacolumbar fracture with pedicle screws at injury level: a biomechanical study based on three-dimensional finite element analysis. Eur J Orthop Surg Traumatol 2013; 23: 775-780.
[14] Dick JC, Jones MP, Zdeblick TA. A biomechanical comparison evaluating the use of intermediate screws and cross-linkage in lumbar pedicle fixation. J Spinal Disord 1994; 7: 402-407.
[15] Mahar A, Kim C, Wedemeyer M, Mitsunaga L, Odell T, Johnson B, Garfin S. Short-segment fixation of lumbar burst fractures using pedicle fixatoin at the level of the fractrue. Spine 2007; 32: 1503-1507.
[16] Phan K, Rao PJ, Mobbs RJ. Percutaneous versus open screw fixation for treatment of thoracolumbar fractures: systematic review and meta-analysis of comparative studies. Clin Neurol Neurosurg 2015; 135: 85-92.
[17] Roy-Camille R, Saillant G, Mazel C. Internal fixation of the lumbar spine with pedicle screw plating. Clin Orthop Relat Res 1986; 203: 7-17.
[18] Feng Y, Chen L, Gu Y, Zhang ZM, Yang HL, Tang TS. Restoration of the spinopelvic sagittal balance in isthmic spondylolisthesis: posterior lumbar interbody fusion may be better than posterolateral fusion. Spine J 2015; 15: 1527-1535.
[19] Krag MH, Beynnon BD, Pope MH. An internal fixator for posterior application to short segments of the thoracic, lumbar, or lumbosacral spine. Design and testing. Clin Orthop Relat Res 1986; 203: 75-98.
[20] Weinstein JN, Rydevik BL, Rauschning W. Anatomic and technical considerations of pedicle screw fixation. Clin Orthop Relat Res 1992; 284: 34-46.