Observational Study

Medicine®

OPEN

Extent and location of fixation affects the biomechanical stability of short- or long-segment pedicle screw technique with screwing of fractured vertebra for the treatment of thoracolumbar burst fractures

An observational study using finite element analysis

Hongwei Wang, PhD[a,b,c,d,*], Zhongjun Mo, PhD[e], Jianda Han, PhD[b], Jun Liu, PhD[a], Changqing Li, PhD[f], Yue Zhou, PhD[f], Liangbi Xiang, PhD[a], Lei Yang, PhD[g,*]

Abstract

Intermediate screw fixation at the fracture level has been widely accepted to treat thoracolumbar burst fractures, but no study has shown the effect of the extent and location of fixation. The effect of the extent and location of fixation on short- or long-segment pedicle screw fixation through intermediate screw fixation at the fracture level in the treatment of thoracolumbar burst fractures is discussed.

Posterior intermediate screw fixation techniques in treating T12 vertebral fracture models were simulated and compared using finite element methods; the fixation techniques included M3-L1 (bilateral 3 monoaxial pedicle screw fixation from L1 to T11), M3-L2, M4-L1 (bilateral 4 monoaxial pedicle screw fixation from L1 to T10), M4-L2, M4-L3, and M5-L2 (bilateral 5 monoaxial pedicle screw fixation from L2 to T10). Range of motion (ROM) and largest von Mises stress (LVMS) of the instrumentations were recorded and analyzed.

No significant differences were observed in the mean ROM of all states of motion between the M3-L1 model and the other fixation models except for M5-L2. The LVMS of the pedicle screws and rods all occurred during flexion. The LVMS values of the pedicle screws were larger in the M3-L2 fixation model and M4-L3 fixation model than in the other fixation models. The M3-L1 model presented a significantly smaller mean LVMS of the pedicle screws in all states of motion than the M3-L2 model ($P = .026$). The LVMS values of the rods were larger in the M3-L2 fixation model, M4-L3 fixation model, and M4-L2 fixation model than in the other fixation models. No significant differences were observed in the mean LVMS of the rods in all states of motion among all the fixation models.

When choosing short-segment pedicle screw fixation with the screwing of fractured vertebrae to treat thoracolumbar fractures, we suggest M3-L1 over M3-L2. More severe injuries can be considered to identify an alternative treatment to long-segment monoaxial pedicle fixation constructs such as the M4-L1 and M5-L2 techniques.

Abbreviations: LSPF = long-segment pedicle screw fixation, LVMS = largest maximal von Mises stress, M3-L1 = bilateral 3 monoaxial pedicle screw fixation from L1 to T11, M3-L2 = bilateral 3 monoaxial pedicle screw fixation from L2 to T12, M4-L1 = bilateral 4 monoaxial pedicle screw fixation from L1 to T10, M4-L2 = bilateral 4 monoaxial pedicle screw fixation from L2 to T11, M4-L3 = bilateral 4 monoaxial pedicle screw fixation from L3 to T12, M5-L2 = bilateral 5 monoaxial pedicle screw fixation from L2 to T10, ROM = range of motion, SSPF = short-segment pedicle screw fixation, VMS = von Mises stress.

Keywords: biomechanics, finite element analysis, long-segment fixation, monoaxial pedicle screw, short-segment fixation, thoracolumbar fracture

Editor: Johannes Mayr.

This work was supported by the Foundation of the Liaoning Province Doctor Startup Fund (201601389), the State Key Laboratory of Robotics (2017-O01), the Open Project Program of the State Key Lab of CAD&CG (A1718), the Open Project Program of the State Key Laboratory of Trauma, Burn and Combined Injury (SKLKF201705), and the State Key Laboratory of Materials Processing and Die & Mould Technology (P2018-011).

The authors have no conflicts of interest to disclose.

[a] Department of Orthopedics, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning, [b] State Key Laboratory of Robotics, Shenyang Institute of Automation, Chinese Academy of Science, Shenyang, Liaoning, [c] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, Hubei, [d] State Key Laboratory of Trauma, Burn and Combined Injury, Third Military Medical University, Chongqing, [e] National Research Center for Rehabilitation Aids, Beijing, [f] Department of Orthopedics, Xinqiao Hospital, The Third Military Medical University, Chongqing, [g] Department of Nutrition, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning, China.

[*] Correspondence: Hongwei Wang, Department of Orthopedics, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning 110016, China (e-mail: cplawhw@163.com); Lei Yang, Department of Nutrition, General Hospital of Shenyang Military Area Command of Chinese PLA, Shenyang, Liaoning 110016, China (e-mail: cplayss@163.com).

Medicine (2018) 97:26(e11244)

Received: 27 September 2017 / Accepted: 22 May 2018

http://dx.doi.org/10.1097/MD.0000000000011244

1. Introduction

Thoracolumbar fractures account for approximately 90% of all spinal fractures, and 10% to 20% of thoracolumbar fractures are burst fractures.[1–5] Short-segment pedicle screw fixation (SSPF) has been beneficial in the management of thoracolumbar spinal fractures. In current studies, posterior intermediate screw fixation at the fracture level can help improve and maintain the kyphosis correction, and the biomechanical stability can also be increased compared with SSPF.[1–15]

There are many studies that compare the biomechanical characteristics and clinical results of SSPF constructs and long-segment pedicle screw fixation (LSPF) constructs without fixation of the fracture level (2 levels above and below of the fractured vertebra).[16–21] Fixation of the fracture level in an SSPF for thoracolumbar fractures yields similar results as LSPF, such as kyphosis correction and maintenance of the sagittal alignment. This technique saves more vertebral motion segments for the patients.[17] SSPF may suffice for stable burst fractures. More severe injuries may benefit from fracture screws, which can be considered as an alternative treatment to LSPF constructs.[19] Fixation at 2 or 3 levels above and 1 level below is as effective as LSPF with respect to the treatment of thoracolumbar fractures (such as correction loss), kyphosis recurrence, and patient satisfaction, and may save 1 lumbar segment.[21]

The objective of the present study was to discuss the effect of the extent and location of fixation on short- or long-segment pedicle screw fixation through intermediate screw fixation at the fractured level in the treatment of thoracolumbar burst fractures. The fixation models, namely, M3-L1 (bilateral 3 monoaxial pedicle screw fixation from L1 to T11); M3-L2, M4-L1 (bilateral 4 monoaxial pedicle screw fixation from L1 to T10); M4-L2, M4-L3, and M5-L2 (bilateral 5 monoaxial pedicle screw fixation from L2 to T10), were simulated and compared with regard to the range of motion (ROM) and von Mises stress (VMS) of the instrumentations.

2. Materials and methods

The procedure was approved by the Ethics Committee of Xinqiao Hospital, the Third Military Medical University of Chinese PLA on September 10, 2010; the project approval number was 20100030.

2.1. Finite element models and implants

A finite element model including 7 vertebrae and 6 discs between T9 and L3 of the spine obtained from 64 spiral computed tomography (CT) images of a 40-year-old healthy male (65 kg and 175 cm) without a history of spinal injury, osteoporosis, and radiographic evidence of degeneration was reconstructed and analyzed using finite element analysis software.[8,22–24] The CT images were scanned and imported into Mimics 10.0 (Materialise, Belgium). The surface model was then exported into Rapidform 2006 (INUS, Korea) to generate and enhance the quality of the solid model. Eventually, the model was imported into Abaqus 6.9 (Simulia) for meshing. Each vertebral body consisted of cortical bone and cancellous bone, and each vertebral disc was composed of nucleus pulposus, annulus fibrosus, and endplates. Posterior elements were built separately from the vertebral bodies. Based on a Boolean operation, the lower half of the T12 segment was resected, and the structure of the posterior part was reserved to establish a finite element model of an unstable thoracolumbar fracture. Surface-to-surface contact was defined between articulation facets. We have built the intact normal spine model and fractured spine model (Fig. 1).

The screw diameter was 6 mm, and the screw length was 45 mm. The pedicle screws in the present study were monoaxial pedicle screws. We have built different fixation models such as M3-L1, M3-L2, M4-L1, M4-L2, M4-L3, and M5-L2 (Fig. 2). The element types, material properties, ligamentary cross-sectional area, and implants are shown in Table 1. The model without implants had a total of 72,055 elements and 20,924 nodes.

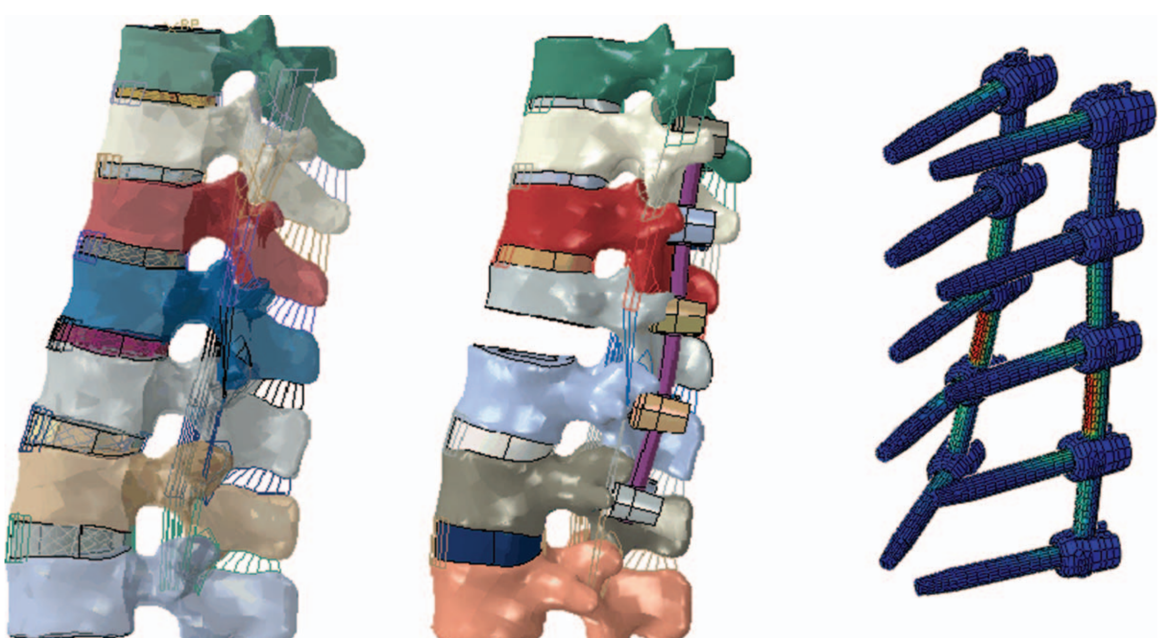
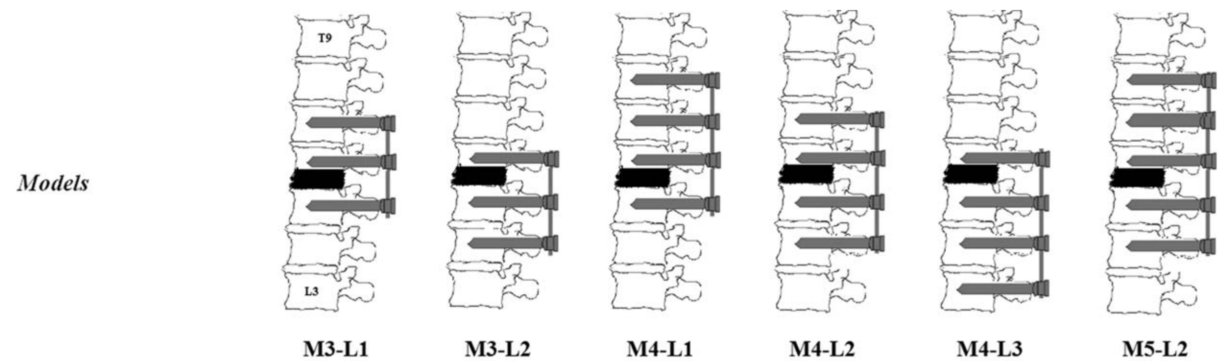


Figure 1. Finite element models: intact model, fracture and fixation model, pedicle screw model.



	M3-L1	M3-L2	M4-L1	M4-L2	M4-L3	M5-L2
State of motion	*flexion*	*flexion*	*flexion*	*flexion*	*flexion*	*flexion*
Level	*lower adjacent*	*fractured*	*lower adjacent*	*fractured*	*fractured*	*fractured*
Pedicle screws (*MPa*)	182.9	287.1	188.4	141.2	283.8	117.5
Rods (*MPa*)	263.2	359.4	259.9	335.1	351.8	272.3

Figure 2. Schematic diagram showing fixation models and the LVMS of pedicle screws and rods according to different fixation models, states of motion and levels.

2.2. Finite element analysis

The finite element analysis was performed by Abaqus 6.9 (Simulia). The top surface of T9 was applied by a pure moment of 10 Nm combined with a precompressive load of 150 N.[23],[25] In the previous study,[8] we applied a pure moment of 10 Nm combined with a precompressive load of 150 N to the fixation models and then measured the ROM of the T11-L1 segments; we measured the ROM of the T9-L3 segments in the present study. Our previous study showed that the calculation model presented in this paper is rational.[8] The ROM of the T9-L3 segments and the largest maximal VMS (LVMS) of the pedicle screws and rods were evaluated. The biomechanical characteristics of M3-L1, M3-L2, M4-L1, M4-L2, M4-L3, and M5-L2 fixation models were analyzed and compared with the intact normal spine model. And the biomechanical characteristics of different fixation models were compared between each other.

2.3. Statistical analysis

We used SPSS version 15.0 (SPSS, Inc., IL) to perform all statistical analyses. We assessed the differences in the continuous variables such as values of ROM and LVMS using paired/independent samples *t* test. The difference of values between intact normal spine model and different fixation models was assessed using paired samples *t* test; the difference of values between different fixation models was assessed using independent samples *t* tests. $P<.05$ was considered significant. The continuous variables were shown as the mean ± standard deviation (SD).

Table 1

Material properties in the present FEM has been shown in the table.

Component	Young's modulus, MPa	Poisson's ratio	Cross section, mm^2
Cortical bone and endplate	12,000	0.30	
Cancellous bone	100	0.20	
Annulus	4.2	0.40	
Nucleus pulposus	1	0.49	
Anterior longitudinal ligaments	7.8	0.40	63.7
Posterior longitudinal ligaments	10	0.30	20
Supraspinous/interspinous ligaments	10	0.30	70
Ligamentum flavum	15	0.30	40
Intertransverse ligament	10	0.30	1.8
Capsular ligament	7.5	0.30	30
Pedicle screws and rods	110,000	0.30	

FEM = finite element method.

3. Results

3.1. ROM of the finite element models

All fixation models presented a significantly decreased ROM than the intact normal spine model ($P<.01$) (Fig. 3). The mean ROM of the fixation models in all states of motion was decreased from $(17.2 \pm 3.3)°$ of M3-L2 to $(8.5 \pm 1.7)°$ of M5-L2 with more pedicle screws fixed in the models (Table 2). There were no significant differences in the mean ROM of all states of motion between the M3-L1 model and the other fixation models except for M5-L2 ($P=.048$, $t=2.992$). The M3-L2 model showed a significantly larger mean ROM than the M4-L1, M4-L2, and M5-L2 models (Figs. 4 and 5).

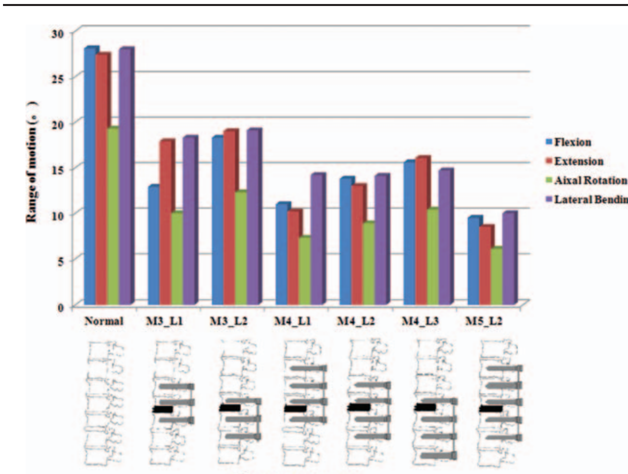


Figure 3. ROM of different models according to different states of motion.

Table 2

The mean ROM of fixation models, the mean LVMS of pedicle screws, and rods of different states of motion have been shown in the table.

Variables	M3-L1	M3-L2	M4-L1	M4-L2	M4-L3	M5-L2
ROM, °	14.8±4.0	17.2±3.3	10.7±2.8	12.5±2.4	14.2±2.6	8.5±1.7
Pedicle screws, MPa	115.6±44.5	185.7±65.0	122.1±44.7	100.7±36.0	184.7±64.6	87.2±26.3
Rods, MPa	168.5±57.0	227.6±93.0	172.4±74.7	185.6±89.6	224.6±89.5	155.7±75.7

M3-L1 = bilateral 3 monoaxial pedicle screw fixation from L1 to T11, M3-L2 = bilateral 3 monoaxial pedicle screw fixation from L2 to T12, M4-L1 = bilateral 4 monoaxial pedicle screw fixation from L1 to T10, M4-L2 = bilateral 4 monoaxial pedicle screw fixation from L2 to T11, M4-L3 = bilateral 4 monoaxial pedicle screw fixation from L3 to T12, M5-L2 = bilateral 5 monoaxial pedicle screw fixation from L2 to T10.

3.2. LVMS of the pedicle screws and rods

The LVMS of the pedicle screws all occurred during flexion (Fig. 1). The LVMS values of the pedicle screws were larger in the M3-L2 fixation model (287.1 MPa) and M4-L3 fixation model (283.8 MPa) than in the other fixation models; the pedicle screws with the LVMS were the ones that were fixed at the fractured level (Figs. 2 and 4). The pedicle screws with the LVMS in the M3-L1 and M4-L1 fixation models were the ones that were fixed at the lower adjacent segment to the fracture level (Fig. 2). The M3-L1 model presented a significantly smaller mean LVMS of pedicle screws in all states of motion than the M3-L2 model ($P=0.026$, $t=-2.458$). The M3-L2 model and M4-L3 model presented a significantly larger mean LVMS of pedicle screws than the other 4 fixation models (Fig. 5) (Table 2).

3.3. LVMS of the rods

The LVMS of the rods all occurred during flexion (Fig. 2). The LVMS values of the rods were larger in the M3-L2 fixation model (359.4 MPa), M4-L3 fixation model (351.8 MPa), and M4-L2 fixation model (335.1 MPa) than in the other fixation models, but there were no significant differences in the mean LVMS of the rods in all states of motion among all the fixation models (Fig. 5) (Table 2).

4. Discussion

Many studies had compared the biomechanical characteristics and clinical results of SSPF constructs and LSPF constructs without fixation of the fractured level.[16–21] However, no studies have compared the biomechanical characteristics of posterior intermediate screw fixation techniques with SSPF and LSPF with regard to the ROM and VMS of the instrumentations, and no studies have shown the extent and location of fixation. In the present study, fixation models showed significantly less ROM than the intact normal spine model, but there was no significant difference in the mean ROM of all states of motion between the M3-L1 model and the other fixation models except for M5-L2. The M3-L2 model showed a significantly larger mean ROM than the M4-L1, M4-L2, and M5-L2 models. The LVMS values of pedicle screws were larger in the M3-L2 and M4-L3 fixation models than in the other fixation models. The M3-L2 model presented a significantly larger mean LVMS of pedicle screws in all states of motion than the M3-L1 model. The M3-L2 model and M4-L3 model presented a significantly larger mean LVMS of pedicle screws than the other 4 fixation models.

Our results were consistent with previous studies, which showed that screws at the fracture level improve construct stiffness. SSPF with the screwing of fractured vertebra at unstable thoracolumbar fracture levels is as effective as LSPF to restore the anterior vertebral height for the treatment of unstable thoracolumbar fractures.[18] Two-levels-above and one-level-below pedicle screw fixation in unstable thoracolumbar burst fractures was useful to prevent progressive kyphosis and preserve one motion segment distally and was as effective as LSPF in terms of correction loss, kyphosis recurrence, and patient satisfaction.[20,21]

The extent and location of fixation affect the biomechanical stability of fixation models. When choosing short-segment pedicle screw fixation with the screwing of fractured vertebrae to treat thoracolumbar fracture, we suggest choosing M3-L1 over M3-L2. More severe injuries can be considered to identify an alternative treatment to long-segment monoaxial pedicle fixation constructs such as the M4-L1 and M5-L2 techniques. Our results also suggested that the M3-L1, M4-L1, and M5-L2 techniques can decrease the LVMS of the instrumentations, and we can see that M3-L1 can save 1 or 2 lumbar segments compared with the M4-L1 and M5-L2 techniques in the treatment of thoracolumbar fractures. More severe injuries can be considered to identify an alternative treatment to LSPF constructs such as M5-L2 techniques. There were no significant differences in the mean LVMS of the rods in all states of motion among all the fixation models. Upon suspecting that a pedicle screw is broken, we must focus on the fractured levels in M3-L2, M4-L3, M4-L2, and M5-L2 techniques and the lower vertebrae adjacent to the fractured levels in M3-L1 and M4-L1.

There were a few limitations to this study. The most common pattern of burst fracture is a fracture between the pedicles in the upper half of the body. In the present study, we attempted to recreate a burst fracture model where only the inferior half of T12 and the intervertebral disc between T12 and L1 were completely

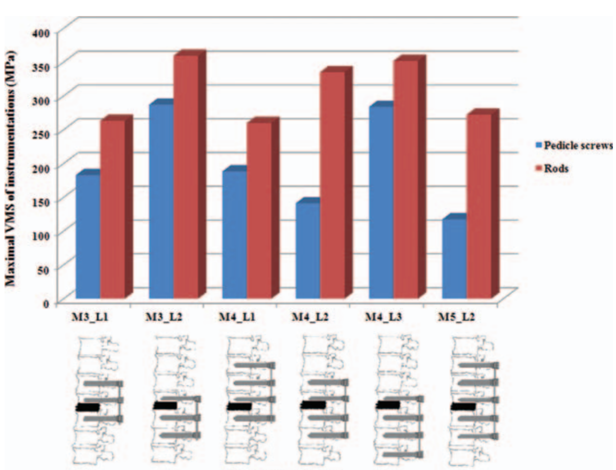


Figure 4. LVMS of pedicle screws and rods according to different fixation models.

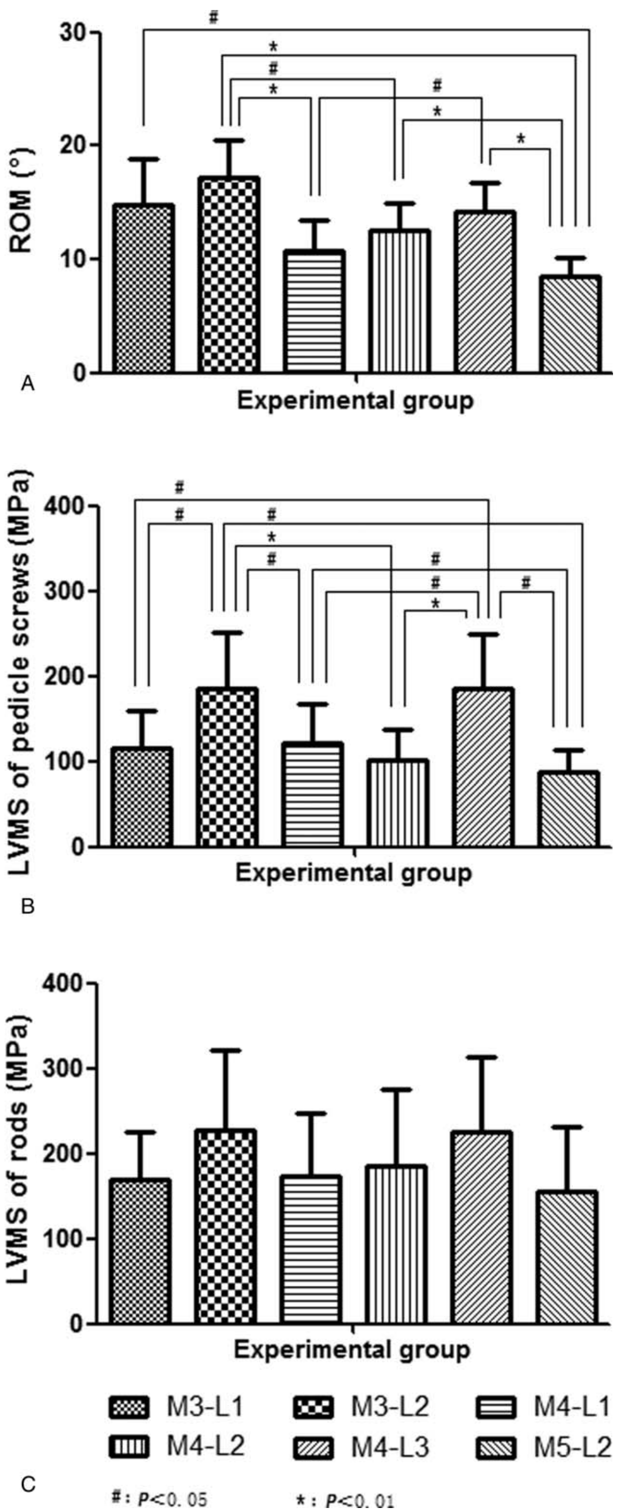


Figure 5. Mean ROM, LVMS of the pedicle screws and rods of different states of motion. (A) Mean ROM the fixation model of different states of motion. (B) Mean LVMS of the pedicle screws of different states of motion. (C) Mean LVMS of the rods of different states of motion.

resected. Possible differences in pedicle dimensions, muscle force, ribs, and screw sizes should be regarded as impact factors in a future study. We did not take polyaxial screws in our study because the location and number of polyaxial screws may affect our results.

We chose the extreme case and carried out our biomechanical study; the conclusions drawn from the study of the extreme spinal fracture model with more severe instability can also provide references for the clinical treatment of type A 3.1 spinal burst fractures.[8] The study can provide much information related to the effect of the extent and location of fixation on the biomechanical stability of short- or long-segment pedicle screw fixation through intermediate screw fixation at the fracture level in the treatment of thoracolumbar burst fractures. We will undertake further research about posterior short-segment intermediate screws fixation techniques with hybrid monoaxial and polyaxial pedicle screws in the near future based on the present study.

5. Conclusion

When choosing short-segment pedicle screw fixation with the screwing of fractured vertebrae to treat thoracolumbar fractures, we suggest M3-L1 over M3-L2. More severe injuries may require an alternative treatment to long-segment monoaxial pedicle fixation constructs, such as the M4-L1 and M5-L2 techniques.

Author contributions

Conceptualization: Hongwei Wang, Jianda Han, Jun Liu, Changqing Li, Yue Zhou, Liangbi Xiang, Lei Yang.
Data curation: Hongwei Wang, Zhongjun Mo, Jianda Han, Changqing Li, Yue Zhou, Liangbi Xiang, Lei Yang.
Formal analysis: Hongwei Wang, Zhongjun Mo, Jianda Han, Yue Zhou, Lei Yang.
Investigation: Jianda Han, Jun Liu, Liangbi Xiang.
Methodology: Zhongjun Mo, Jun Liu, Changqing Li, Lei Yang.
Project administration: Hongwei Wang, Zhongjun Mo, Yue Zhou, Liangbi Xiang.
Resources: Hongwei Wang, Jun Liu.
Software: Zhongjun Mo, Jianda Han.
Supervision: Jianda Han, Jun Liu, Changqing Li, Yue Zhou, Liangbi Xiang, Lei Yang.
Validation: Hongwei Wang, Zhongjun Mo, Jun Liu, Liangbi Xiang, Lei Yang.
Visualization: Hongwei Wang, Jianda Han, Yue Zhou, Lei Yang.
Writing – original draft: Hongwei Wang, Zhongjun Mo, Jun Liu, Changqing Li.
Writing – review and editing: Jianda Han, Yue Zhou, Liangbi Xiang, Lei Yang.

References

[1] Wang H, Zhang Y, Xiang Q, et al. Epidemiology of traumatic spinal fractures: experience from medical university-affiliated hospitals in Chongqing, China, 2001–2010. J Neurosurg Spine 2012;17:459–68.
[2] Wang H, Zhou Y, Ou L, et al. Traumatic vertebral fractures and concomitant fractures of the rib in southwest China, 2001 to 2010: an observational study. Medicine 2015;94:e1985.
[3] Wang H, Liu X, Zhao Y, et al. Incidence and pattern of traumatic spinal fractures and associated spinal cord injury resulting from motor vehicle collisions in China over 11 years: an observational study. Medicine 2016;95:e5220.
[4] Verlaan JJ, Diekerhof CH, Buskens E, et al. Surgical treatment of traumatic fractures of the thoracic and lumbar spine: a systematic review of the literature on techniques, complications, and outcome. Spine 2004;29:803–14.
[5] Shen WJ, Liu TJ, Shen YS. Nonoperative treatment versus posterior fixation for thoracolumbar junction burst fractures without neurologic deficit. Spine 2001;26:1038–45.

[6] Baaj AA, Reyes PM, Yaqoobi AS, et al. Biomechanical advantage of the index-level pedicle screw in unstable thoracolumbar junction fractures. J Neurosurg Spine 2011;14:192–7.
[7] Wang H, Li C, Liu T, et al. Biomechanical efficacy of monoaxial or polyaxial pedicle screw and additional screw insertion at the level of fracture, in lumbar burst fracture: an experimental study. Indian J Orthop 2012;46:395–401.
[8] Li C, Zhou Y, Wang H, et al. 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.
[9] Kanna RM, Shetty AP, Rajasekaran S. Posterior fixation including the fractured vertebra for severe unstable thoracolumbar fractures. Spine J 2015;15:256–64.
[10] Li K, Zhang W, Liu D, et al. Pedicle screw fixation combined with intermediate screw at the fracture level for treatment of thoracolumbar fractures: a meta-analysis. Medicine 2016;95:e4574.
[11] Li K, Li Z, Ren X, et al. Effect of the percutaneous pedicle screw fixation at the fractured vertebra on the treatment of thoracolumbar fractures. Int Orthop 2016;40:1103–10.
[12] Sun C, Guan G, Liu X, et al. Comparison of short-segment pedicle fixation with versus without inclusion of the fracture level in the treatment of mild thoracolumbar burst fractures. Int J Surg 2016;36:352–7.
[13] Sun C, Liu X, Tian J, et al. Comparison of unilateral versus bilateral pedicle screw fixation at the level of fracture using posterior short-segment pedicle instrumentation in the treatment of severe thoracolumbar burst fractures. Int J Surg 2017;41:50–5.
[14] Wang H, Zhou Y, Li C, et al. Comparison of open versus percutaneous pedicle screw fixation using the sextant system in the treatment of traumatic thoracolumbar fractures. Clin Spine Surg 2017;30:E239–46.
[15] Wang H, Zhao Y, Mo Z, et al. Comparison of short segment monoaxial and polyaxial pedicle screws fixation combined with intermediate screws in the traumatic thoracolumbar fractures: a finite element study and clinical radiographic review. Clinics (Sao Paulo) 2017;72:609–17.
[16] McDonnell M, Shah KN, Paller DJ, et al. Biomechanical analysis of pedicle screw fixation for thoracolumbar burst fractures. Orthopedics 2016;39:e514–8.
[17] Dobran M, Nasi D, Brunozzi D, et al. Treatment of unstable thoracolumbar junction fractures: short-segment pedicle fixation with inclusion of the fracture level versus long-segment instrumentation. Acta Neurochir 2016;158:1883–9.
[18] Ozdemir B, Kanat A, Erturk C, et al. Restoration of anterior vertebral height by short-segment pedicle screw fixation with screwing of fractured vertebra for the treatment of unstable thoracolumbar fractures. World Neurosurg 2017;99:409–17.
[19] Bolesta MJ, Caron T, Chinthakunta SR, et al. Pedicle screw instrumentation of thoracolumbar burst fractures: biomechanical evaluation of screw configuration with pedicle screws at the level of the fracture. Int J Spine Surg 2012;6:200–5.
[20] Modi HN, Chung KJ, Seo IW, et al. Two levels above and one level below pedicle screw fixation for the treatment of unstable thoracolumbar fracture with partial or intact neurology. J Orthop Surg Res 2009;4:28.
[21] Ugras AA, Akyildiz MF, Yilmaz M, et al. Is it possible to save one lumbar segment in the treatment of thoracolumbar fractures? Acta Orthop Belg 2012;78:87–93.
[22] Akamaru T, Kawahara N, Sakamoto J, et al. The transmission of stress to grafted bone inside a titanium mesh cage used in anterior column reconstruction after total spondylectomy: a finite-element analysis. Spine 2005;30:2783–7.
[23] Kim Y, Kim TW. Finite element analysis of the effects of pedicle screw fixation nut loosening on lumbar interbody fusion based on the elasto-plateau plasticity of bone characteristics. Spine 2010;35:599–606.
[24] Kim HJ, Chun HJ, Moon SH, et al. Analysis of biomechanical changes after removal of instrumentation in lumbar arthrodesis by finite element analysis. Med Biol Eng Comput 2010;48:703–9.