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The biomechanical advantages of bilateral lumbo-iliac fixation in unilateral comminuted sacral fractures without sacroiliac screw safe channel

A finite element analysis

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Abstract

Background: The aim of this study was to compare the biomechanical characteristics between bilateral and unilateral lumbo-iliac fixation in unilateral comminuted sacral fractures (USF) by finite element analysis.

Methods: A 3-dimensional finite element model of unilateral sacral fractures was simulated. Three kinds of implants were instrumented into the model, including the unilateral lumbopelvic fixation (ULF), bilateral lumbopelvic fixation (BLF), and unilateral iliac fixation with bilateral lumbar pedicle screws (UBF). Loads of compression and rotation were distributed to the superior endplate of L3. To evaluate the biomechanical properties, the construct stiffness, the micromotion of the fractures, the stress distribution of implants, and the balance of hemilumbar vertebra are recorded and analyzed.

Results: The highest construct stiffness was provided by BLF. In BLF model, the displacement between iliums was only 0.009 mm (compressional) and 0.001 mm (rotational), which was less than that under normal condition (0.02 mm). The maximum von Misses stress of implants appeared on the UBF. By using unilateral fixation, the L4 endured obvious imbalance on bilateral hemivertebra. A marked difference was exposed in BLF and UBF models, and the equilibrium of stress and activity was shown.

Conclusion: From the finite element view, the stability of ULF is insufficient to reconstruct the posterior pelvic ring. Furthermore, the unilateral fixation may lead to imbalance of lumbar vertebra and pelvis. On the contrary, the BLF can provide satisfied stability and lumbar balance.

Abbreviations: BLF = bilateral lumbopelvic fixation, Nor = normal, UBF = unilateral iliac fixation with bilateral lumbar pedicle screws, ULF = unilateral lumbopelvic fixation, USF = unilateral comminuted sacral fractures.

Keywords: biomechanical characteristics, finite element analysis, lumbo-iliac fixation, sacral fractures

1. Introduction

Unilateral sacral fractures are uncommon injury caused by high energy,[1] for which the most common reason is lateral compression. Anatomically, the connection between spine and hemipelvis is interrupted. As we know, the sacrum plays an important role in the posterior pelvic ring which can transfer the body weight from spine to the lower extremities. Therefore, surgical treatment should be performed after unstable sacral fractures, especially in patients with nerve damage. The purpose of surgery is not only to achieve reduction and fixation of the sacral fractures, but also to restore the biomechanical stability and the gravity transmission line.

Lumbopelvic fixation was improved in 1998 by Schildhauer et al.[2,3] In the biomechanical tests,[4,5] this method can provide satisfied reduction and rigid fixation for sacral fractures. Moreover, lumbo-iliac fixation can reconstruct the spine–pelvic biomechanical transduction pathway. Based on the above advantages, lumbo-iliac fixation has become popular and performed satisfactory curative effect.[6,7] However, various lumbo-iliac fixation techniques were mixed. Schildhauer et al[3] recommended lumbopelvic fixation using a double pedicle rod construct with a cross-link or a single pedicle rod construct with an iliosacral screw. Keel et al[8] performed unilateral lumbopelvic fixation (ULF) in a consecutive series of 10 patients with sacral fractures. This less invasive technique provided ample stabilization and reduced complications such as infection, hematoma, etc. Similarly, Saigal et al[9] applied a lumbopelvic method with unilateral iliac screw and bilateral lumbar pedicle screws. In his retrospective study, unilateral versus bilateral iliac screws led to comparable rates of reoperation, iliac screw removal, postoperative infection, pseudarthrosis, and sacral insufficiency fractures. Yu et al study[10] claimed that dual-iliac screws can provide more strength and higher stability than a single-iliac screw. In severe cases, S1 and S2 sacroiliac screws' safe insertion space was completely destroyed. To enhance the stability, the lumbopelvic stabilization method was used instead of iliosacral screw fixation.

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There is a conventional consideration that unilateral sacral fractures are regarded as unilateral injury, and unilateral lumbo-iliac fixation is performed logically. Whereas, many surgeons believe that bilateral lumbopelvic fixation (BLF) can provide more stability. Furthermore, BLF can avoid stress and activity imbalance of hemivertebra and hemipelvis. Sagi et al[11] have demonstrated that ULF may lead to sagittal plane deformity. Despite the theoretical differences, it remains unclear that lumbopelvic fixation technique is superior from biomechanical view.

Thus, the aim of this study was to compare the biomechanical characteristics between bilateral and unilateral lumbo-iliac fixation in the treatment of unilateral comminuted sacral fractures (USF) without sacroiliac screws safe channel by finite element analysis. The biomechanical behavior was evaluated by construct stiffness, displacement of fracture zone, stress distribution, and the maximum von Misses stress of implants. With respect to lumbar and pelvic disorders, we focused on the equilibrium of stress and activity.

2. Methods

Permission for this study was obtained from the Medical Ethics Committee of Shandong Provincial Hospital Affiliated to Shandong University.

2.1. Finite element models and implants

An intact 3-dimensional finite element model of L3-pelvis was used to simulate the normal (Nor) condition (Fig. 1B). To simulate the worst situation, the model of USF was made by a one-third bone defect from Nor model (Fig. 1A).

Three implants were instrumented into the USF model, including the ULF, BLF, and unilateral iliac fixation with bilateral lumbar pedicle screws (UBF) (Fig. 1A). The length and diameter of lumbar pedicle screw and iliac screw (Medtronic-WeiGao Inc., WeiHai, China) were 45 mm, 6.5 mm and 70 mm, 7.5 mm, respectively. The iliac screws and lumbar pedicle screws were instrumented into the USF model according to the standard surgical technique. Six lumbar pedicle screws were performed at the L3–L5 level, and 2 parallel iliac screws were inserted from the posterior superior iliac spine to the anterior inferior iliac spine at each ilium. The pedicle-screw/pedicle-screw and pedicle-screw/iliac-screw were connected by 2 longitudinal rods. Contralateral longitudinal rods were fixed by 2 cross-links which were set at the L3–L4 and L5–ilium levels. The threads of pedicle screws and iliac screws were omitted in order to simplify the models. The model without implants had a total of 952,964 elements and 249,366 nodes. The number of elements for implants was 63,355 for ULF, 135,622 for BLF, and 97,783 for UBF, respectively. The number of nodes for implants was 15,013 for ULF, 32,000 for BLF, and 23,094 for UBF, respectively.

2.2. Finite element analysis

The finite element analysis was performed by Abaqus 6.13 (Simulia, Providence, RI). Linear elastic isotropic material properties were assigned to all models and implants. The ligaments were simulated as nonlinear spring elements. The properties of bones, ligaments, annulus, nucleus, and implants are shown in Table 1. Bilateral acetabulum of models was fixed. The contact behavior of screw/longitudinal-rod interfaces was set as rigid bond. For fixation, the implants were locked to the bone. All contact elements were defined as deformable elements. The analysis was performed under the frictionless mode to simplify the contact phenomena.

Loads of compression and rotation were applied at all models (Fig. 1B). For the compression, a vertical force of 600 N was distributed to the superior endplate of L3. For rotation, a

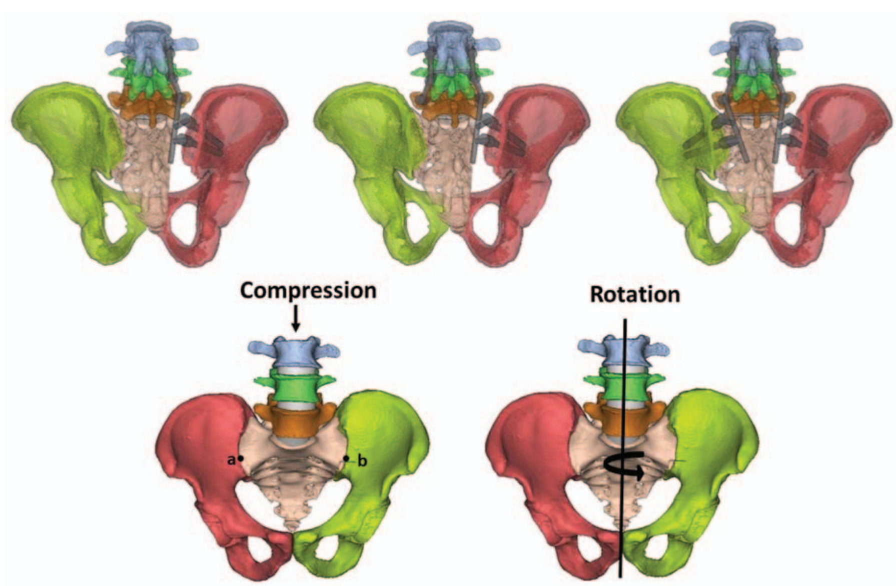

Figure 1. (A) The model of unilateral sacral fractures was made by a one-third vertical bone defect from intact L3-pelvis model. Three kinds of implants were instrumented into the unilateral sacral fractures model, including the ULF, BLF, and UBF. (B) An intact L3-pelvis model simulated the normal condition. Two points were defined at right and left ilium to measure the distance of posterior pelvic ring. For the compression, a vertical force of 600 N was distributed to the superior endplate of L3. For rotation, a follower load of 100 N and a torque of 7 Nm were applied to the superior endplate of L3 around the spinal mechanical axis to simulate the function of right rotation. BLF = bilateral lumbopelvic fixation, UBF = unilateral iliac fixation with bilateral lumbar pedicle screws, ULF = unilateral lumbopelvic fixation.

Table 1

Material properties of finite element method (FEM) models.

Material	Elastic modulus, MPa	Poisson ratio	Cross-section area, mm^2	K, N/m	Number of springs
Bone					
Cortical bone	18,000	0.3			
Cancellous bone	200	0.2			
Disc					
Annulus	8.4	0.45			
Nucleus	Mooney–Rivlin c1 = 0.12, c2 = 0.03				
Ligaments					
Anterior longitudinal ligament	7		63.7		
Posterior longitudinal ligament	7		20		
Ligamentum flavum	3		40		
Intratransverse ligament	7		1.8		
Capsular ligament	4		30		
Interspinous ligament	6		40		
Supraspinous ligament	6.6		30		
Anterior and capsule sacroiliac ligament				700	27
Posterior sacroiliac ligament				1400	15
Interosseous sacroiliac ligament				2800	8
Iliolumbar ligament				2800	30
Sacrospinous ligament				1400	9
Sacrotuberous ligament				1500	15
Superior pubic ligament				500	24
Arcuate pubic ligament				500	24
Implants	114,000	0.3			

follower load of 100 N and a torque of 7 Nm were applied to the superior endplate of L3 around the spinal mechanical axis to simulate the function of right rotation.

The biomechanical characteristics of BLF, ULF, and UBF models were analyzed and compared to the Nor model. The construct stiffness was obtained to compare the construct stability. To evaluate the stability of sacrum, the maximum vertical displacements were recorded. The stability of the fractures zone was evaluated by the displacement of the posterior pelvic ring. Two points were defined at bilateral iliums to measure the distance of posterior pelvic ring (Fig. 1B). To evaluate the force condition, the stress distribution and the maximum von Misses stresses were described. The displacement and stress distribution of hemi-L4 vertebra was displayed to observe lumbar balance under compressive load.

3. Results

3.1. Construct stiffness

The compressive stiffness of the ULF, BLF, and UBF models are shown in Table 2 and Fig. 2A. The BLF model showed the highest compressive construct stiffness, especially at the right ilium. With regard to the sacrum, there was no significant difference among the 3 techniques. The rotational stiffness of the ULF, BLF, and UBF models are shown in Table 2 and Fig. 2B. A similar result was found for construct stiffness. Under compressive and rotational stiffness, the highest construct stiffness of implants appeared on BLF.

3.2. Fracture displacements

Table 3 schematically shows displacements of the fracture zone. In general, the BLF provided the strongest stability of the posterior pelvic ring. The distance of AB was 85.965 mm without load. Using bilateral fixation, the distance between iliums under compressive and rotational load was 85.956 and 85.964 mm, respectively, which was less than that under Nor condition (89.965 mm).

The maximum vertical displacements of sacrum are shown in Table 3. The maximum vertical displacement significantly reduced (at least 85%) by using lumbopelvic fixation. But, there was no significant difference among the 3 fixation methods.

Table 2

The construct stiffness of models.

Construct	Compressional stiffness, %				Rotational stiffness, %			
	Nor	ULF	BLF	UBF	Nor	ULF	BLF	UBF
L3	100	84.828	102.618	87.469	100	52.233	63.595	52.233
L4	100	74.262	96.611	79.290	100	52.853	75.536	57.516
L5	100	64.178	81.591	66.702	100	63.134	82.530	65.238
Sacrum	100	37.431	39.828	38.929	100	20.930	23.000	21.600
Ilium R	100	70.000	131.683	80.851	100	34.375	49.205	42.308
Ilium L	100	47.039	65.000	47.906	100	31.395	45.000	32.661

BLF = bilateral lumbopelvic fixation, Nor = normal (condition), UBF = unilateral iliac fixation with bilateral lumbar pedicle screws, ULF = unilateral lumbopelvic fixation.

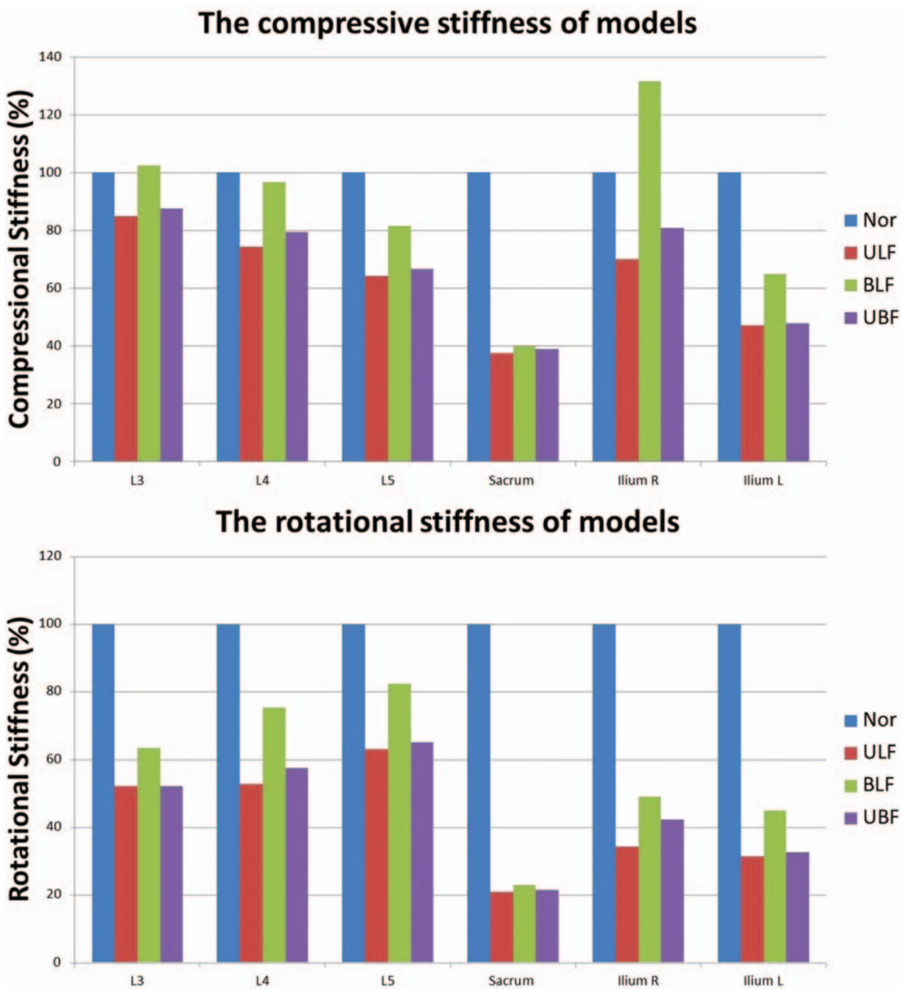

Figure 2. Compressive and rotational construct stiffness under different circumstances. The bilateral lumbopelvic fixation (BLF) model showed the highest compressive construct stiffness, especially at the right ilium and L3. The BLF model showed the highest rotational construct stiffness.

3.3. The von Misses stress distribution

The stress distribution of pelvic ring is described in Figs. 3 and 4 through the 3 fixation methods. Under compressive load circumstance, the maximum von Misses stress of implants appeared on the L4–L5 and L5–ilium levels of the longitudinal rods (Fig. 3). Under rotational load circumstance, the upper of right longitudinal rod connecting L5 pedicle screw and iliac screws endured the maximum stress (Fig. 4). The maximum von Misses stress on UBF was greatest compared with BLF and ULF.

3.4. The stress and activity equilibrium of L4

Under compressive load condition, the stress and activity balance of L4 is revealed in Fig. 5. By using unilateral fixation, the L4

Table 3

The displacements of models.

Construct	Compressional load				Rotational load			
	Nor	ULF	BLF	UBF	Nor	ULF	BLF	UBF
L3	3.567	4.205	3.476	4.078	0.421	0.403	0.331	0.403
L4	2.366	3.186	2.449	2.984	0.352	0.333	0.233	0.306
L5	1.272	1.982	1.559	1.907	0.274	0.217	0.166	0.210
Sacrum	0.749	2.001	1.980	1.924	0.054	0.129	0.180	0.125
Sacrum (vertical)	0.609	0.090	0.063	0.084	–	–	–	–
Ilium R	0.266	0.380	0.202	0.329	0.022	0.032	0.039	0.026
Ilium L	0.286	0.608	0.440	0.597	0.081	0.129	0.090	0.124
Posterior pelvic ring (increment displacement)	0.020	0.067	0.009	0.063	0.004	0.014	0.001	0.014

BLF = bilateral lumbopelvic fixation, Nor = normal (condition), UBF = unilateral iliac fixation with bilateral lumbar pedicle screws, ULF = unilateral lumbopelvic fixation.

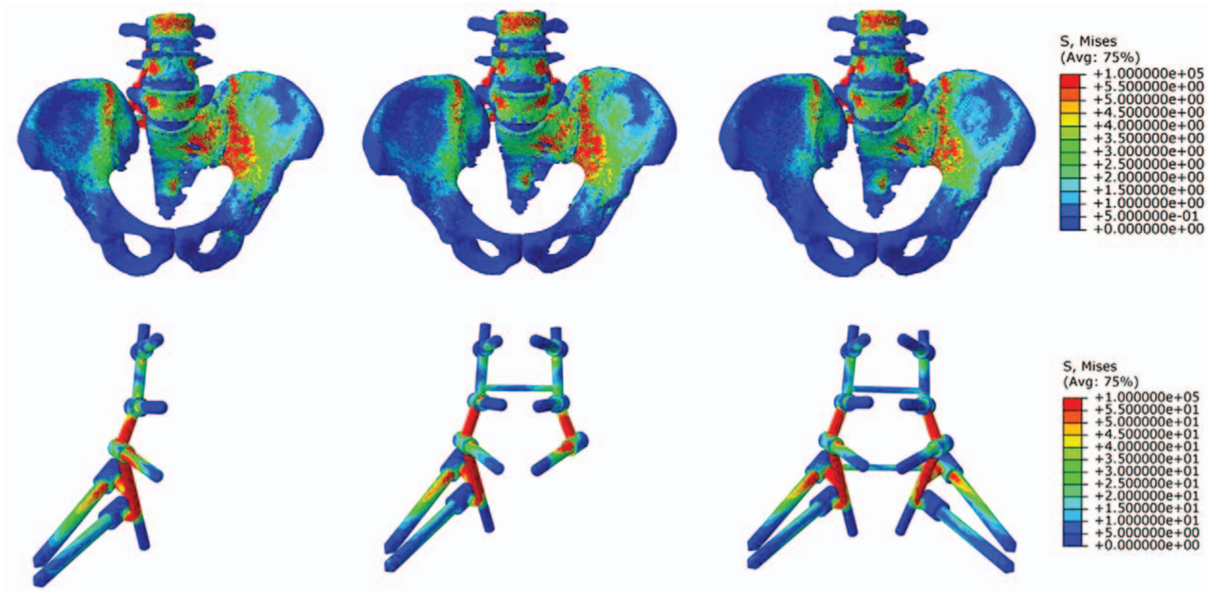

Figure 3. The stress distribution of pelvic ring was described under compressive load. The maximum von Misses stress of implants appeared on the L4–L5 and L5–ilium levels of the longitudinal rods.

lumbar vertebra endured obvious imbalance on bilateral hemivertebra. A marked difference was noted between BLF and UBF models, regarding the equilibrium of stress and activity.

4. Discussion

Unilateral sacral fractures are uncommon. The instability of the posterior pelvic ring is always caused by this injury. There are several internal fixation methods to treat sacral fractures,[1,12,13] such as iliosacral screws, transiliac rods, and locking compression plate. Unfortunately, these conventional methods cannot achieve sufficient strength and appropriate fractures reduction.[14–16] The lumbopelvic fixation seems appropriate to solve these problems, which is firmly enough to provide postoperative stability immediately.[3] Biomechanically, the lumbopelvic fixation can transfer the body weight from spine to the acetabulum directly in order that the gravity transmission line bypasses the fractures site to promote fracture union.

With respect to the multiplanar and bilateral sacral fractures, BLF is performed definitely, especially with spinopelvic dissociation. However, whether bilateral or unilateral fixation should be applied for unilateral sacral fractures has not been studied

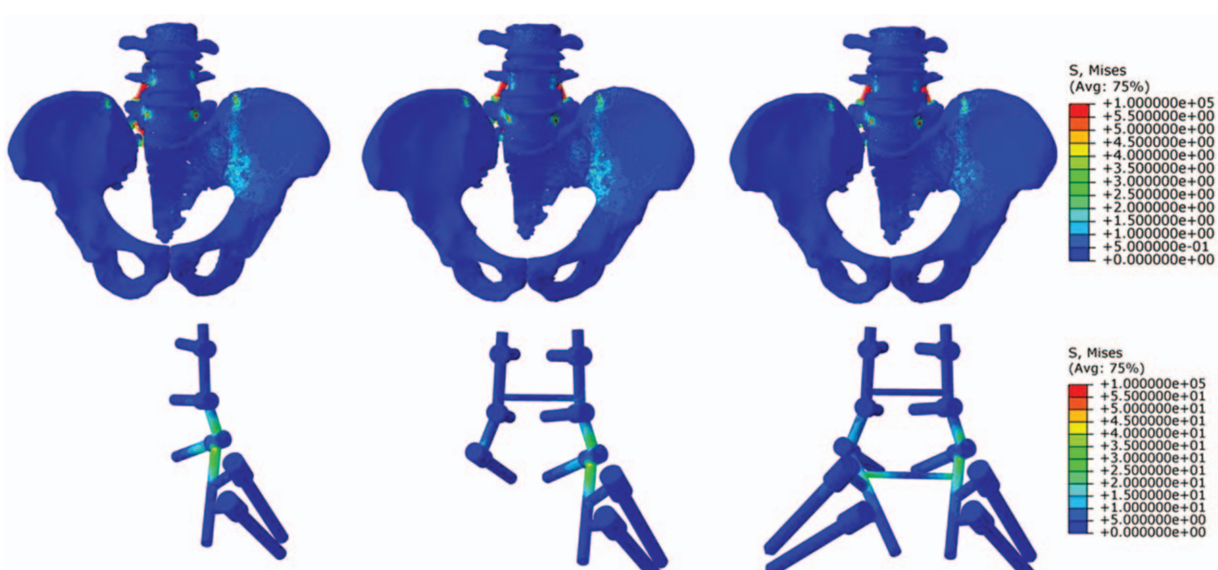

Figure 4. The stress distribution of pelvic ring was described under rotational load. The upper of right longitudinal rod connecting L5 pedicle screw and iliac screws endured the maximum stress.

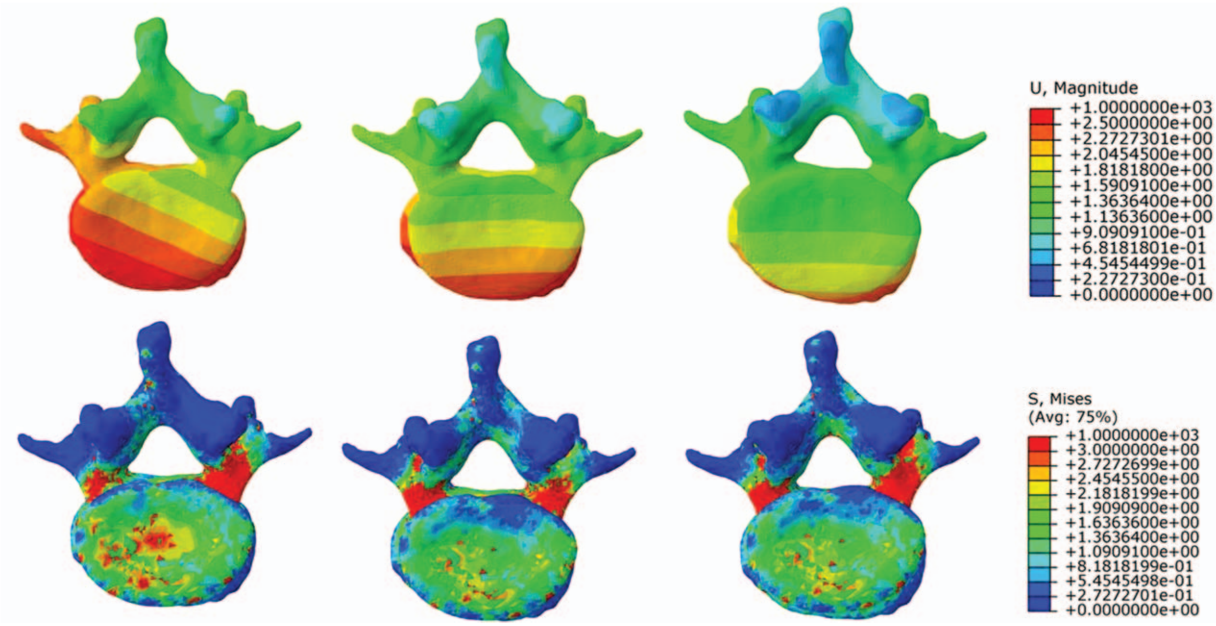

Figure 5. Under compressive load condition, the L4 lumbar vertebra endured obvious imbalance on bilateral hemivertebra by using unilateral fixation. A markedly difference was exposed in BLF and UBF models, the equilibrium of stress and activity were shown. BLF = bilateral lumbopelvic fixation, UBF = unilateral iliac fixation with bilateral lumbar pedicle screws.

systematically. Theoretically, a significant increase of stability is obtained by bilateral fixation. Two cross-links are employed to connect BLF into a 3-dimensional monolithic construction. In horizontal, coronal, and sagittal plane, fractures are reduced and fixed so that the fracture zone resists vertical and rotational shear forces. On the contrary, the ULF cannot resist 3-dimensional rotational shear force. A supplementary iliosacral screw can provide more stability. But in the most severe unilateral sacral fractures, the fracture line is massively comminuted so that lumbopelvic fixation with sacral screw or iliosacral screw would be impeded. To address this problem, a dual-iliac screws technique is performed for compensatory stability. From Yu et al biomechanical study,[10] the dual-iliac screws technique achieved much higher construct stability than a single iliac screw technique. Saigal et al[9] applied a lumbopelvic method with unilateral pelvic fixation and bilateral lumbar vertebra fixation. In his clinical retrospective study, unilateral iliac fixation was recommended to grade II or higher L5–S1 spondylolisthesis, long-segment fusions to the sacrum and L5–S1 pseudarthrosis. However, this method provides a novel treatment for sacral fractures.

Under the conditions of comminuted fractures, posterior malreduction, sacral dysmorphism, and sacral neural decompression, sacroiliac screw is not easy to perform. In our study, a one-third vertical bone defect was made from intact L3-pelvis model to simulate the severe unilateral sacral fractures with complete destruction of the S1 and S2 sacroiliac screws' safe insertion space. Therefore, we did not investigate the biomechanical characteristics of the lumbopelvic fixation with sacroiliac screw. The right anterior sacroiliac ligament, posterior sacroiliac ligament, and interosseous sacroiliac ligament were transected to simulate the most severe sacroiliac joint injury and dislocation. The unilateral sacral fractures always involve an injury of anterior pelvic ring. There is no doubt that injury of the anterior pelvic ring fractures affect stability of the pelvis. To set the single factor, we simulated an intact anterior pelvic ring.

Although Keel et al study[8] claimed that ULF can provide the required stability, our results revealed that ULF cannot provide enough horizontal and rotational stability. BLF model showed the highest construct stiffness and the minimum displacement compared with ULF and UBF models. Under compressive load condition, the micromotion of the fracture zone was 0.02, 0.009, 0.067, and 0.063 mm in Nor, BLF, ULF, and UBF models site of implant failure, respectively. A similar result was found under rotational load condition. These results may be attributed to the fact that BLF can constitute a 3-dimensional stability mechanism to resist rotational and multiplanar shear force. Moreover, delayed union and nonunion of the sacral fracture are caused by unfavorable reduction and fracture instability.[11] The BLF allows 3-plane reduction to achieve adequate compression.

With regard to rotation, the intact model was considered a 2 part model: spine and pelvis. Relative to the rotational spine, pelvis is a solid foundation. Therefore, the junction of spine and pelvis is the potential site of implant failure. According to our results, the upper of right longitudinal rod connecting lumbar verterbra and pelvis endured the maximum stress. The maximum vertical compression von Misses stress was 464.361, 645.801, and 702.039 MPa in ULF, BLF, and UBF, respectively. The maximum rotational von Misses stress was similar. In general, the risk of screw loosing and hardware failure depends mainly on a large amount of stresses on implants. The unilateral fixation had a tendency to plastic yielding and fatigue cracking, as can be explained by the situation that the spine was intact and the pelvis was insufficiently fixed.

The ULF is a less invasive technique, resulting a lower rate of complications should be decreased. However, a tendency that some patients felt discomfort of waist and hip after ULF was noted in our daily work. The complaints were barely mentioned by patients with bilateral fixation. So, we supposed that ULF impaired the balance of the lumbar spine and pelvis region. This finite element analysis verified our hypothesis. In consideration, the unilateral sacral fractures disturbed the equilibrium of pelvis, we chose L4 to estimate the equilibrium of stress and activity. As a result, the stress and activity of L4 displayed intense imbalance in ULF. BLF and UBF provided sufficient equilibrium. Furthermore, although ULF is a less invasive technique, the soft tissue was destructed inevitably on 1 side. This is a possible reason for spinal imbalance, degeneration, chronic lower back pain, and pelvic pain.[17] Sagi et al[11] declared that the lumbopelvic scoliosis and tilting of the L5 vertebra were occurred after improper reduction and unilateral fixation. The unilateral fixation seems to be vulnerable to maintain structural balance. To achieve better long-term results, BLF or ULF with tension band plate should be performed on the patients with unilateral sacral fractures to distribute the force better.

There are some limitations in this study. The finite element models were based on skeleton-ligament system and the muscle forces were neglected, similarly to other finite element studies. A single lumbar–pelvic model was used for analysis which may avoid the high variation rate of bone and ligament characteristics. The present fracture models cannot simulate all the real situations; however, this model can still provide much information related to USF. This finite element study has only evaluated the early postoperative stability, but the long-term biomechanical stabilization has not been analyzed. Considering these limitations, the conclusions should be studied using clinical retrospective analysis and cadaver biomechanical testing to determine the feasibility. The conclusions should be carefully used in clinical practice.

In conclusion, the stability of ULF is insufficient to reconstruct the posterior pelvic ring from the finite element viewpoint. Furthermore, the unilateral fixation may lead to imbalance of lumbar vertebra and pelvis, chronic lower back pain, delayed union, and nonunion. On the contrary, the BLF can provide sufficient stability and lumbar balance.

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