

Biomechanical Study of Lumbar Spine using Unilateral Pedicle Screw with Tadpole Fixation System*

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Abstract

The purpose of this study was to investigate the biomechanical stability of unilateral pedicle screw and rod system fixation (unilateral PS fixation) using the Tadpole system fixation for an unstable lumbar spine. We used 5 lumbar spines (L3/4) of a functional spinal unit (FSU) obtained from wild boar cadaver specimens. Damage or instrumentation was sequentially administered to each specimen, and 6 models were prepared: (1) an intact model, (2) an injury model with facet joint resection, (3) a unilateral PS fixation model, (4) a bilateral PS fixation model, (5) a Tadpole system fixation model, and (6) a combination of the unilateral PS and Tadpole system fixation models. We conducted a bending test in 8 directions by using a 6-axis material tester, and the range of motion (ROM) of each model in all directions was measured. The ROM of the combined fixation model of the unilateral PS and Tadpole system was considerably decreased in all directions. These findings indicate that the combination unilateral PS and Tadpole system fixation is a minimally invasive method that has the same stability as bilateral PS fixation.

Key words: Unilateral Pedicle Screw and Rod System, Tadpole System, Minimally Invasive Surgery, Spine Biomechanics, Unstable Lumbar Spine

1. Introduction

The pedicle screw and rod system (PS system), that is one of surgical methods for posterolateral lumbar spinal fixation, is the spinal instrumentation expected to confer very high stability to the lumbar spine^{(1),(2)}. In particular, in cases of severely unstable lumbar spine resulting from disease, bilateral PS fixation is used to insert 2 PSs from both lateral

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sides of the affected spine.

Recently, minimally invasive surgery (MIS) has been frequently performed because it helps reduce both operative duration and intraoperative bleeding. To surgically correct lumbar alignment or to improve bone fusion, various MIS methods have been used, including unilateral posterior lumbar interbody fusion (unilateral PLIF), transforaminal lumbar interbody fusion (TLIF), and percutaneous pedicle screw insertion. Shin et al. have reported that unilateral PLIF using 2 cages showed almost favorable clinical results in 41 patients⁽³⁾ and Toyone et al. have reported a reduction in operative duration, amount of intraoperative bleeding, and severe complications such as nerve root injuries⁽⁴⁾. However various instrumentation failures have still not been reported. Percutaneous PS insertion can achieve MIS; however, nerve root injuries caused by accidental screw insertion have been reported⁽³⁾⁻⁽⁸⁾.

The unilateral PS fixation system in which a single PS system has been applied to only the lateral side of the spine has been attempted to achieve MIS (Fig. 1(a),(b)). However, this system can result in uneven constraints depending on the bending direction of the lumbar spine^{(9),(10)}. Therefore this system has firm constraint of the lumbar spine in only particular direction.

On the other hand, spinal instrumentation using spinal processes as anchors has been clinically utilized for approximately 50 years; examples of this instrumentation include the Daab plate and the Wilson plate. The recently developed S plate, the Lumbar Alligator Spinal system, and CD HORIZON SPIRE™ spinous process plate (Medtronic Inc.) have been reported to facilitate operation and reduce the amount of intraoperative bleeding and frequency of complications^{(11),(12)}. Spinal instrumentation using spinal processes as anchors can be used for MIS without the risk of screw insertion into the vertebral body⁽¹¹⁾⁻⁽¹⁵⁾.

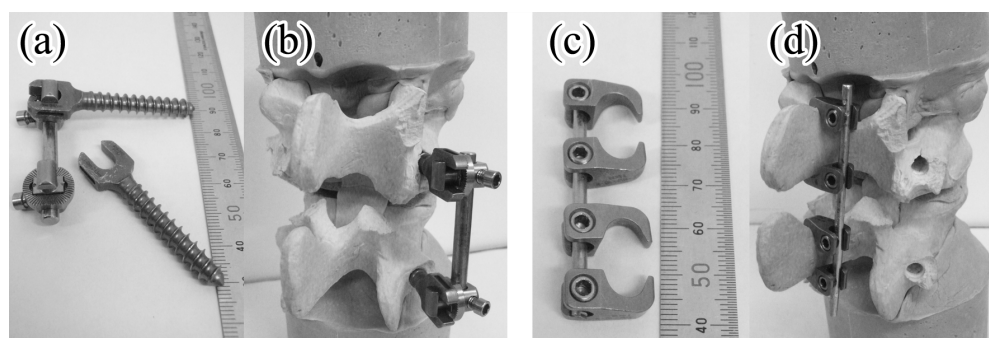


Fig. 1 Spinal instrumentations and surgical methods for posterolateral lumbar spinal fixation: (a) pedicle screw and rod system (PS system) and (b) unilateral PS fixation; (c) Tadpole system and (d) Tadpole fixation.

Favorable results of MIS have been reported from the use of the Tadpole system for lumbar fixation⁽¹³⁾ (Fig. 1(c),(d)). This system involves new spinal instrumentation in which the spine can be stabilized using 2 sets of 2 spinal processes as fixation anchors. Kasai et al. reported that in the 31 patients who underwent spinal fusion using the Tadpole system, the operative duration decreased to average 8 min. The postoperative improvement rate of the Japanese Orthopaedic Association (JOA) score for lumbar spinal disorders on a 29-point scale before and 2 years after operation was on average 73.9%⁽¹³⁾. Moreover, no complications such as spinal fluid leakage, nerve root injuries, or postoperative infection are observed, and 2 years after the operation, the bone union rate is 93.5%⁽¹³⁾. However, the Tadpole system has to be placed in a specific direction to firmly fix the affected lumbar spine. Therefore, the Tadpole system is difficult to apply in cases of excessive and severe instability of the affected lumbar spine, even though it can be used in cases of moderate instability because of the uneven fixation for the bending direction, which is similar to that

in the unilateral PS fixation system.

More favorable fixation is achieved using a combination of the unilateral PS fixation system and the Tadpole system because the combined system gives firmly fixation for any directions. In this study, biomechanical constraints using a combination of the unilateral PS fixation system and the Tadpole system were experimentally investigated.

2. Experimental methods

Five lumbar spines, L3–L4, of a functional spinal unit (FSU) obtained from the lumbar spine of the cadavers of female wild boar between 3 and 4 of age were used as specimens. Both the ends of each FSU, from which the muscle and fat tissues had been removed, were thawed at room temperature, mounted with dental resin, and placed on an attachment. Six experimental models were prepared from each FSU (Fig. 2). The experimental models included (1) an intact model without damage and controls; (2) an injury model prepared by drilling 5-mm holes from 3 directions (front, diagonal, and lateral directions) in the intervertebral disc, by notching the supraspinal and interspinal ligaments, and by total resection of both sides of the intervertebral joint; (3) a unilateral PS fixation model prepared using PS fixation on the right side of the injury model; (4) a bilateral PS fixation model prepared using PS fixation on the left side of the unilateral PS fixation model; (5) a Tadpole system model prepared using the Tadpole system of the injury model; and (6) a combination fixation model prepared using the Tadpole system of the unilateral PS model.

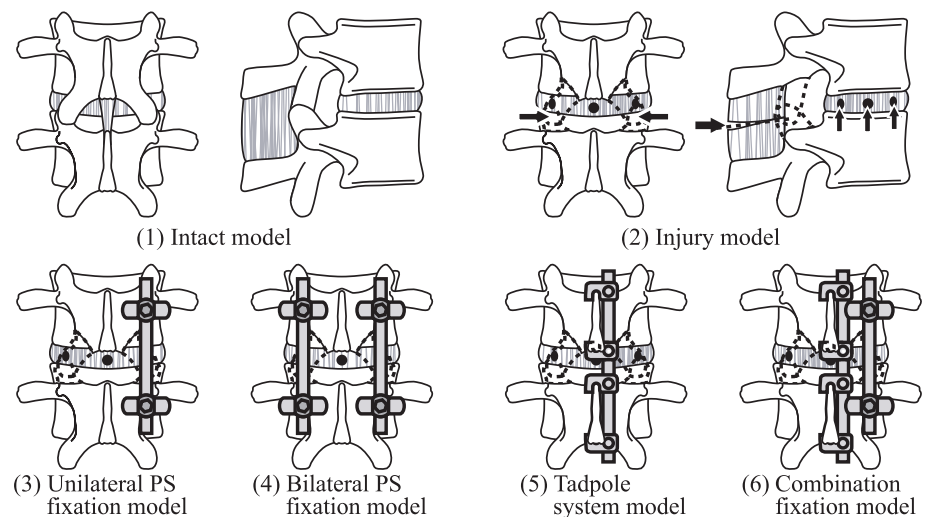


Fig. 2 Experimental models: (1) intact model, (2) injury model with damaged intervertebral disk, supraspinal and interspinal ligaments, and total resection of bilateral intervertebral joint; (3) unilateral PS fixation model reconstructed with the single PS system; (4) bilateral PS fixation model reconstructed with the bilateral PS system; (5) Tadpole system model reconstructed with a Tadpole system; and (6) combination model reconstructed with the Tadpole system and the unilateral PS system.

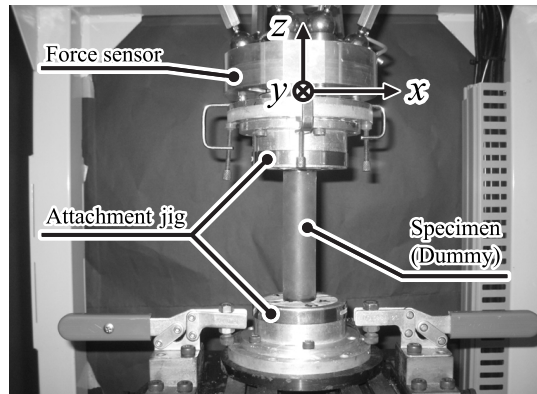


Fig. 3 Six-axis material testing machine.

A 6-axis material tester was used as a biomechanical measurement device (Fig. 3)^{(15)–(17)}. This testing device employs a vertical, linear, and parallel motion mechanism by placing a set of 2 linear actuators in parallel and in symmetry at 120°. Each of these 6 linear actuators is independently controlled. The 6-axis force sensor in the tip of the moving arm enables detection of the load along the x-, y-, and z-axes and the torque of each axis rotation. Furthermore, the force can be controlled using the feedback of the detected values to the control system. On the basis of the above mechanism, this testing device can produce optional three-dimensional degrees of freedom of movement.

A bending test under 3 degrees of freedom was carried out using the 6-axis material tester by attaching each experimental model under 3 degrees of freedom. Under this condition, pure bending occurs in the plane perpendicular to a selected axis, and it is generated by bending the specimen to the load moment around the selected axis and by restricting translational motion along the axis and bending motion around the other axes. In the bending test, the specimen was subjected to varying torque ranging from -3 Nm to 3 Nm at an angular velocity of 0.1 s^{-1} in 8 directions (Fig. 4), including the forward, backward, left, right, and oblique directions.

Each bending movement was repeated 3 times to exclude alterations in the motion of the FSU because of its viscoelastic effect by using its relaxation. Therefore, the range of motion (ROM) calculated from the third movement was used to compare the biomechanical properties of each model (Fig. 5). ROM was defined as the rotary angle of the upper vertebral body of the FSU in the torque–rotary angle curve obtained from the bending test under maximum torque ($\pm 3 \text{ Nm}$). A torque of $\pm 3 \text{ Nm}$ was set so that all experimental models reached the elastic zone after exceeding the neutral zone. In each bending test, displacement, angular displacement, force, and torque generated in each axis were measured and stored in a personal computer in a sampling period of 1Hz.

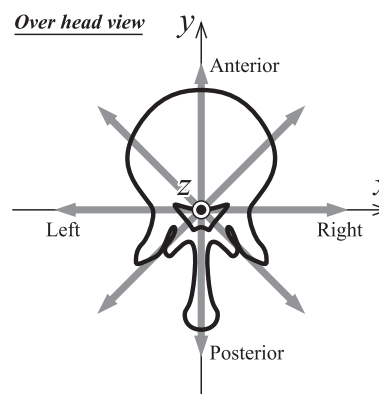


Fig. 4 Bending directions.

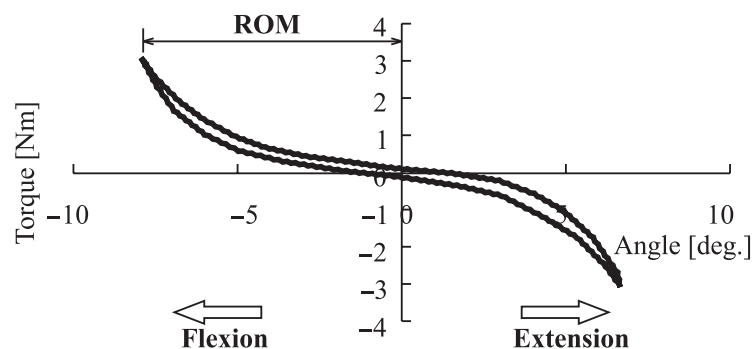


Fig. 5 Typical example of torque and rotary angle of intact FSU bending.

3. Experimental results

Table 1 shows the averages and standard deviations of ROMs obtained from the bending tests for each model, together with statistical significance. The significance of results of each fixation model based on the injured model was approved by the pair T test because all fixation models were derived from the injured model step by step. Fig. 6 shows the average of ROMs in each model for different bending directions.

According to Table 1 and Fig. 6, the ROMs expanded in all directions for the injury model, but not in the intact model, and the ROMs in the bilateral PS fixation model contracted to approximately half of the intact model, or one-third of the injury model in all directions. The ROMs in the left anterior and right posterior directions of the unilateral PS fixation models have values similar to that of the bilateral PS fixation model. Additionally, ROMs on the anterior, posterior, left, and right directions decreased to approximately half of that in the injury model. However, the ROMs in the right anterior and left posterior directions of the unilateral PS fixation model were the same as those of the injury model. The torque–rotary angle curve for the ROMs of the unilateral PS fixation model had a tilted elliptic shape in which an obvious difference was present depending on the direction.

The ROMs in the posterior and anterior directions of the Tadpole system model contracted in a manner similar to those of the bilateral PS fixation model, even though the ROMs in the left and right directions were nearly the same as those in the injury model.

The ROMs in the anteroposterior and lateral directions in the combination fixation model using the Tadpole system and unilateral PS fixation was substantially lower than in the injury model. Moreover, these ROMs were lower than those of the intact model.

Table 1 ROM of each model obtained using a bending test in 8 directions.

	(1) Intact	(2) Injured model	(3) Unilateral PS fixation model	(4) Bilateral PS fixation model	(5) Tadpole system fixation model	(6) Combination fixation model
Flexion	7.4±2.4	11.6±2.1	** 4.5±1.2	* 6.3±1.6	** 3.0±0.8	** 3.3±1.3
Extension	7.2±1.8	10.5±2.2	** 4.0±1.5	** 5.6±2.2	** 2.4±1.2	** 1.9±0.5
Left lateral	7.1±2.0	11.4±2.4	** 3.6±1.6	* 7.0±1.4	9.8±1.1	* 6.0±1.4
Right lateral	6.9±2.3	9.1±1.6	** 3.5±1.7	* 6.3±2.0	* 8.5±1.6	* 5.7±1.8
Left anterolateral	7.4±1.7	10.3±1.2	** 4.5±1.5	** 5.0±1.2	** 4.6±1.2	** 3.6±0.7
Right anterolateral	7.6±2.1	10.2±1.6	** 3.5±0.8	9.7±1.0	** 4.2±0.6	** 4.1±1.0
Left posterolateral	7.4±1.4	10.2±1.6	** 4.0±1.2	10.8±1.1	** 4.1±1.7	** 3.8±1.5
Right posterolateral	6.9±1.9	9.3±2.1	** 3.6±1.5	** 3.9±1.4	** 3.6±1.6	** 2.7±1.0

* P<0.05 vs. Injured model ** P<0.01 vs. Injured model

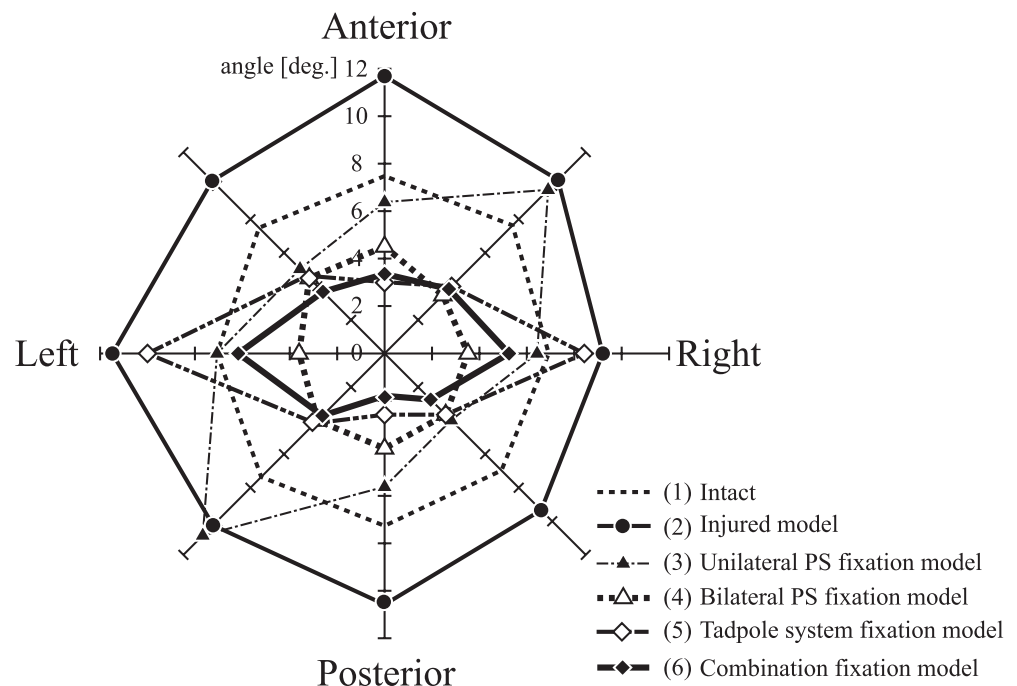


Fig. 6 Average of ROM of each model in 8 directions.

4. Discussion

According to the results of the bending tests, fixation of the Tadpole system and unilateral PS fixation system was found to depend on the bending direction, whereas the bilateral PS fixation system achieved stable and strong fixation in all directions.

In the Tadpole system, all directions except in the right and left directions in the lumbar spines were fixed as firmly as in the bilateral PS fixation system. The Tadpole system strongly and selectively restrains the spines from bending in the anterior, and posterior directions because this system hooks the spinal processes behind the spines used as anchors and the rigid rod supported by a pair of hooks acts as a beam that suppresses FSU bending from the rear of the spine. The Tadpole system uses two pairs of hooks to fasten both ends of spinal processes, but it allows for a perpendicular rotating motion toward the rod at a contact point between the hook and the spinal process. Therefore, there is little effect on the restriction of lateral bending even though fixation in the anterior and posterior directions is improved.

However, the unilateral PS fixation system firmly restricts the motion of FSU in the direction of screw insertion and offers a slight constraint to motion in the perpendicular direction. This direction-dependent, uneven constraint of the unilateral PS fixation system is caused by the effect of the rod, which acts as a rigid beam similar to the one in the Tadpole system, and the slight freedom of rotation offered to the screw inserted into the vertebral body.

It is important that the directions constrained selectively by the Tadpole system are different from those constrained by the unilateral PS fixation system. The Tadpole system and unilateral PS fixation system can compensate for each other. The combination fixation model achieved constraint equal to that achieved by the bilateral PS fixation model independent of the bending direction.

This suggests that the unilateral PS fixation system reduces significantly the risk of complications caused by accidental screw insertion in comparing with the bilateral PS fixation system. Additionally, the combination of the unilateral PS fixation and Tadpole system without screw insertion into the vertebral body can confer constraints similar to

those conferred by the bilateral PS fixation system in cases of severe instability of the lumbar spine caused by total resection of the intervertebral joint. To investigate a clinical and more practical model, such as a hemifacetectomy model, a combination of the unilateral PS fixation system and Tadpole system can be used for cases in which MIS is necessary, for example, in operations on elderly individuals.

5. Conclusion

In this study, the biomechanical stability of lumbar spines fixed using a combination of the unilateral PS fixation system and Tadpole system was investigated. The experimental results suggest that a combination of these fixation systems can reduce the burden on patients undergoing MIS and induce firm constraints nearly equal to those in the conventional bilateral PS fixation system used for treating severe instability of lumbar spines.

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