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Biomechanical Effects of Fixation of Different Segments of Goat Lumbar Spine on Adjacent Segmental Motion and Intradiscal Pressure Change

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Background: The aim of this study was to investigate the biomechanical fixation effects of different segments of the goat spine on adjacent segmental motion and intradiscal pressure (IDP) change.

Material/Methods: Eighteen goat spine specimens were randomly divided into 3 groups: group A (single-segment fixation), group B (double-segment fixation), and group C (triple-segment fixation). The motion was tested on each specimen using a spinal motion simulation test system with rational pressure loading. The IDP was measured using a pinhole pressure sensor.

Results: Range of motion (ROM) and IDP of adjacent segments increased with increased external load. In comparison of the 3 groups, significant differences in ROM were found when the external force was more than 100 N ($P<0.05$). The differences in IDP of the adjacent segment were statistically significant ($P<0.05$) when external pressure was greater than or equal to 60 N. However, in comparison of group A with group B, no significant differences in ROM and IDP of the adjacent segments were noted for the motions of anterior flexion, posterior extension, and lateral bending ($P>0.05$). Moreover, upper adjacent segments had greater ROM than the lower adjacent segments ($P<0.05$). We found significant differences between IDPs of the upper adjacent segments and lower adjacent segments ($P<0.05$).

Conclusions: As the number of fixated lumbar segments increases, ROM and IDP of the adjacent segments increase. Multisegment fixation is most likely the main factor contributing to the development of adjacent segmental lesions after lumbar fixation.

MeSH Keywords: **Biomechanical Phenomena • Intervertebral Disc Degeneration • Orthopedic Fixation Devices**

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Background

Chronic low back pain is the most common symptom of lumbar degenerative disease [1]. Surgery is an effective treatment for patients for whom conservative treatments are ineffective and for those with severe neurological symptoms. For patients with lumbar degenerative disease and lumbar instability, lumbar internal fixation with fusion is often used. With the increase in the number of clinical cases and the length of follow-up, adjacent segment degeneration (ASD) has become an important factor for patients who undergo secondary surgery. ASD caused by the stress shielding and by the loss of lumbar motion due to multisegment fixation is an important factor that can produce long-term clinical effects [2,3]. Although the exact incidence and mechanism of development of ASD remain unclear, there is evidence that the high incidence of ASD after surgery is associated with rigid internal fixation and fusion [3–5].

To help prevent ASD caused by multisegment fixation, some researchers advocate the use of selective short-segment internal fixation; this not only solves the problem of lumbar stability, but also maintains a physiological range of motion similar to that of a normal spine. This approach offers an advantage in preserving the physiological motion range of the lumbar spine. However, lumbar degenerative disease of multiple segments often occurs. Even if it is limited to single or double segments, accompanying degeneration of the adjacent upper/lower segments is very common. Thus, short-segment fixation is not an effective measure in all cases. Importantly, few studies have addressed the biomechanical fixation effects of different segments of the lumbar spine on adjacent segments, and very few such studies have been conducted using animal models.

The goat spine model has good similarity to humans and is considered a good biomechanical model of the human lumbar spine [6]. Therefore, the aim of this study was to investigate the biomechanical effects of the fixation of different segments of the goat lumbar spine on the adjacent segmental motion and intradiscal pressure (IDP) tested by applying different pressures and mechanical loads in different directions.

Material and Methods

Experimental material

Eighteen spine specimens (T12–S1) from goats 12 to 24 months of age were selected. All specimens were obtained within 2 h after sacrifice of animals and were examined by X-ray to exclude abnormal physiological structures or deformities. Then, they were wrapped in wet gauze, sealed in plastic bags, and stored frozen at –20°C.

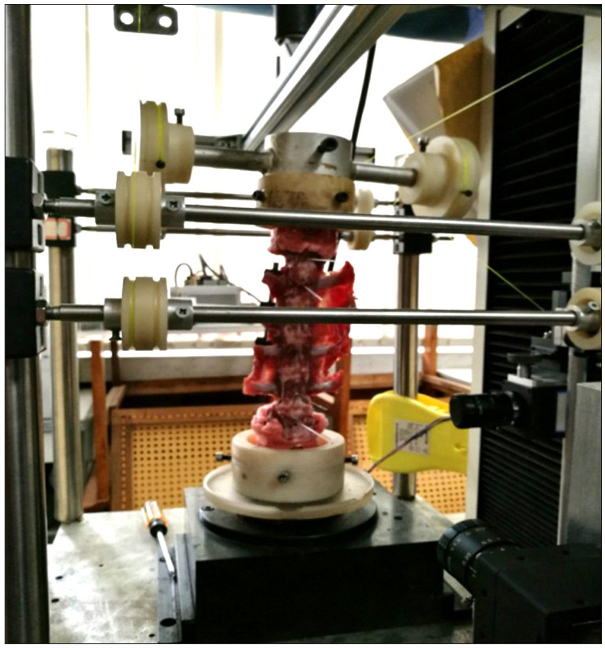

Figure 1. Experimental equipment.

The specimens were removed from the –20°C freezer 24 h prior to the experiment and allowed to thaw naturally at room temperature. The paravertebral muscles were stripped, but the interspinous ligament, supraspinous ligament, intervertebral disc, and vertebral body were preserved intact. Denture base polymer (Shanghai Beiqiong Tooth Co.) was prepared and used to embed L1 and the tailbone. The specimens were numbered. The internal fixation materials (Shandong Weigao Group) included pedicle screws (diameter, 5.5 mm; length, 35 mm), titanium rods (diameter, 5.0 mm; length, 60 mm, 90 mm, and 120 mm), and 9 boxes of bone cement. The experimental equipment included a spinal motion simulation test system manufactured by Shimadzu Corporation and a pinhole pressure sensor (Figure 1).

Establishing and grouping the experimental models

The 18 experimental specimens were randomly divided into 3 groups (A, B, and C) with 6 specimens in each group. The standard posterior lumbar internal fixation technique was performed for these specimens. Group A was a single-segment fixation group in which 4 pedicle screws (5.5×35 mm) were placed on both sides of the L4 and L5 vertebral bodies with placement of titanium rods (5.0×60 mm). Group B was a double-segment fixation group in which 6 pedicle screws (5.5×35 mm) were placed on both sides of the L4, L5, and L6 vertebral bodies with placement of titanium rods (5.0×90 mm). Group C was a 3-segment fixation group in which 8 pedicle screws (5.5×35 mm) were placed on both sides of the L2, L3, L4, and L5 vertebral bodies with placement of titanium rods (5.0×120 mm). The successful specimen model and its X-ray imaging are shown in Figure 2.

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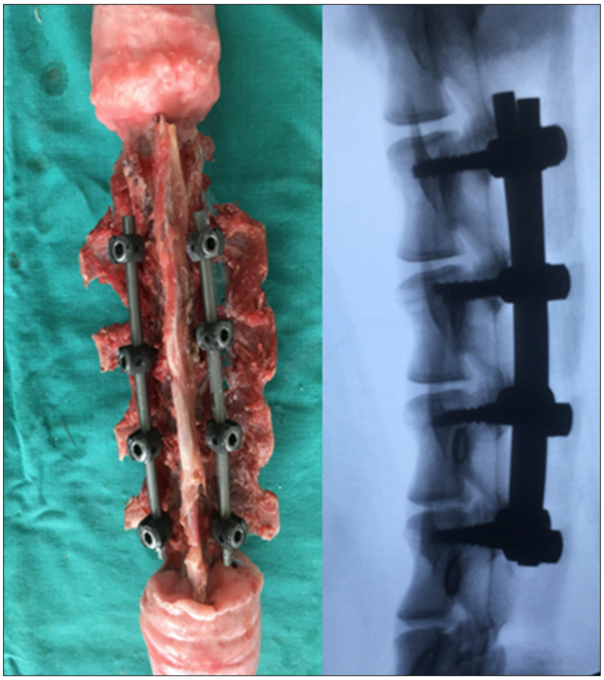


Figure 2. Successful specimen model and its X-ray imaging.

Experimental protocol

Test of the range of motion of the lumbar spine: Motion in 3 directions, including anterior flexion, posterior extension, and lateral bending, was tested on each specimen in group A with loading of 5 different axial external forces (50 N, 80 N, 100 N, 120 N, and 150 N) followed by observation and measurement (with conversion) of the transverse displacement, the forward-backward displacement, and the vertical displacement of the upper and lower adjacent segments. The same method was used to test the biomechanics of the specimens in groups B and C, and the relevant data were recorded.

Test for IDP: The neutral position of the spine specimen was used for pressure loading. The IDP was tested using a pinhole pressure sensor. The upper and lower parts of the specimen were embedded in embedding powder and mounted in the clamp of the test system. Water was sprayed on the thawed specimen every 5 min to prevent dehydration and degradation of the specimen [7]. The experimental environment was maintained at a relatively constant temperature of approximately 23°C. The peripheral temperature was monitored in real time. X-ray radiography was performed to assess the intactness of each specimen before and after testing. The corresponding pressure values were observed and recorded under 5 external loads (20 N, 40 N, 60 N, 80 N, and 100 N). Figure 3 shows the definition of direction of motion during the testing process.

This study protocol was reviewed and approved by the authors' institutional ethics committee. The principles of the Helsinki Declaration served as the ethical guidance for implementation of this study.

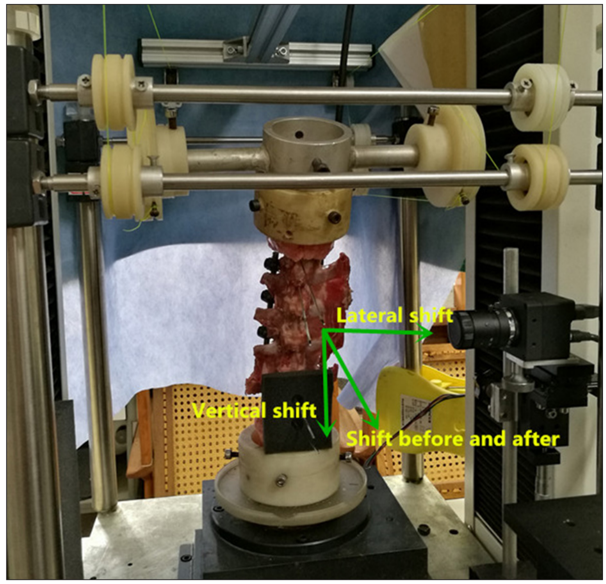
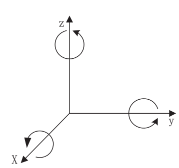


Figure 3. Definition of direction of motion during the testing process.

Camera calibration and coordinate conversion

Two cameras were used in the experiments; the left and right cameras were individually calibrated. The diameter of the calibration ball was 1.45 mm. According to the relationship between the physical size of the calibration ball and the pixel size, the physical/pixel ratio in the current experiment was obtained and used to calculate the actual displacement according to the imaging method.

In this study, some images were taken from a 45° viewing angle (left and right viewing angles). To unify the images according to the three-dimensional coordinate transformation formula, the rotation transformation around the Z axis (vertical direction, i.e., the reverse direction of the Y axis in the acquired images) is shown as follows:



Its transformation matrix is as follows:

$$T_{RZ} = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

where the angle (θ) is 45° (clockwise), i.e., the transformation matrix is as follows:

$$T_{RZ} = \begin{bmatrix} \frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 & 0 \\ -\frac{\sqrt{2}}{2} & \frac{\sqrt{2}}{2} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calibration results: the diameter of the small ball, which has a physical diameter of 1.45 mm, is 110 pixels; thus, the physical size of each pixel is 1.45 mm/110. The displacement is approximately 0.013200 mm.

The displacement of the observation point was input into the transformation formula, and the formula was used to calculate the forward-backward displacement, the transverse displacement, and the vertical displacement.

Statistical methods

SPSS 17.0 software was used for statistical analysis. Measurement data are expressed as mean ± standard deviation (SD). Quantitative data are expressed as the mean ±SD. The data for groups A, B, and C were pairwise compared by one-way analysis of variance (ANOVA). The test level was set at $\alpha=0.05$. $P<0.05$ was considered statistically significant.

Results

Range of motion and IDP of adjacent segments increased with the increase of external load (Figures 4, 5). In the comparison

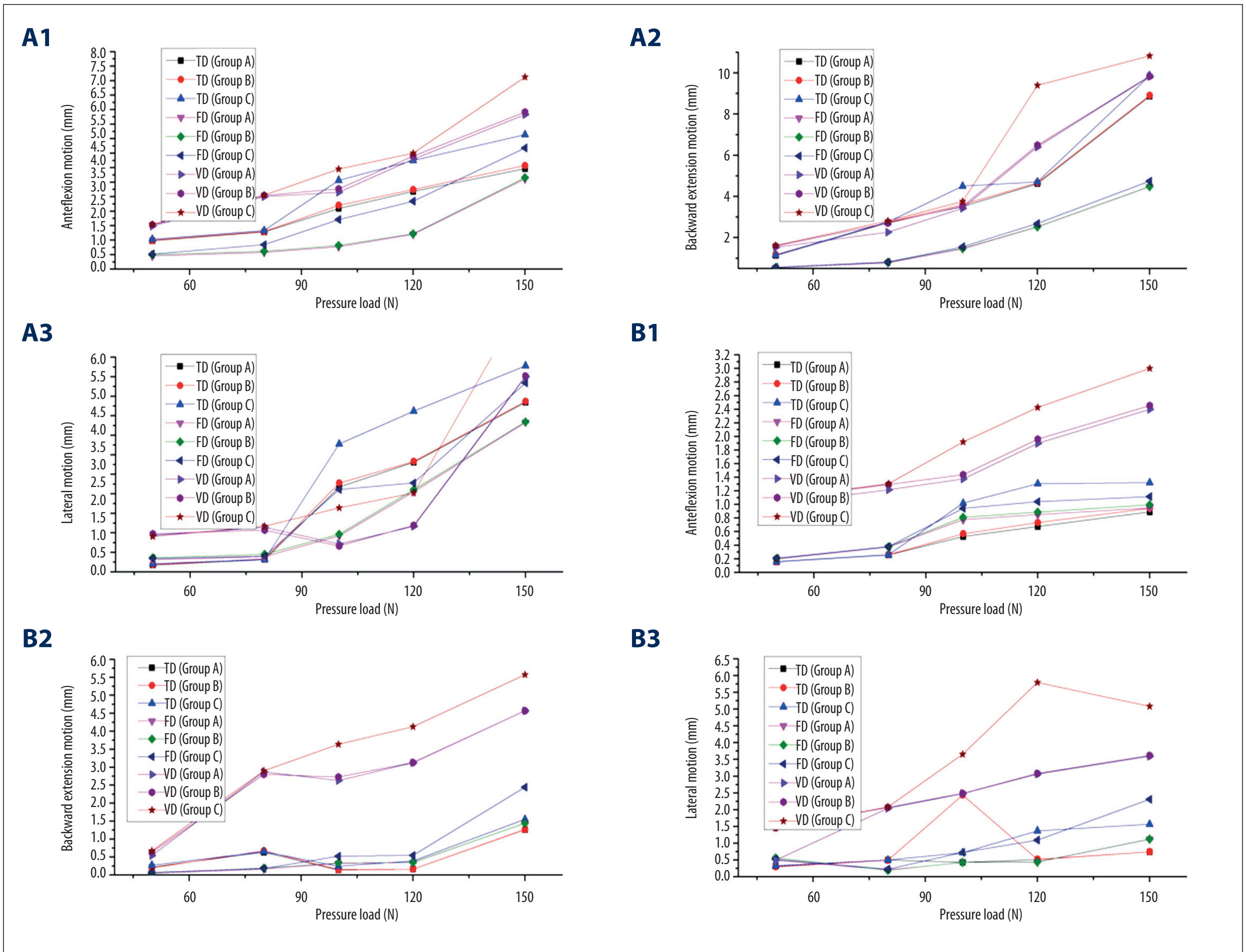


Figure 4. Measurement results of transverse displacement, forward-backward displacement, and vertical displacement in different motion directions, TD – transverse displacement; FD – forward-backward displacement; VD – vertical displacement; **A1, A2, A3** represent TD, FD, and VD at the upper adjacent segments, respectively; **B1, B2, B3** represent TD, FD, and VD at the lower adjacent segments, respectively.

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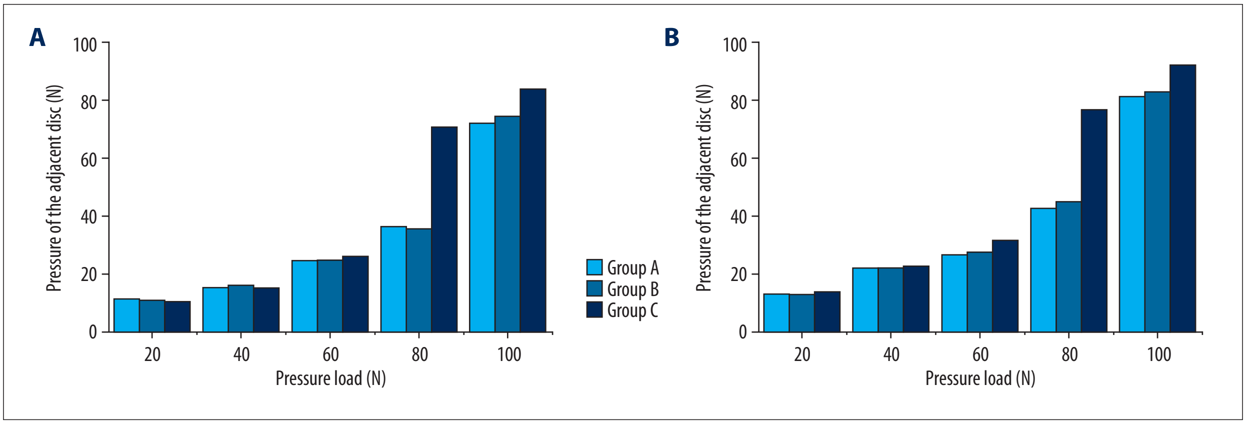

Figure 5. The adjacent segmental IDP. (**A**) IDP at the upper adjacent segments; (**B**) IDP at the lower adjacent segments.

of 3 groups for motions of anterior flexion, posterior extension, and lateral bending, the differences in transverse displacement, forward-backward displacement, and vertical displacement of the adjacent segments were not statistically significant when the external force was less than or equal to 80 N (P>0.05), but were statistically significant when the external force was more than 100 N (P<0.05). The differences in IDP of the adjacent segment were statistically significant (P<0.05) when the external pressure was greater than or equal to 60 N.

In the comparison of group A with group B, no significant differences in motion range and IDP of the adjacent segments were noted for the motions of anterior flexion, posterior extension, and lateral bending (P>0.05). However, there were statistically significant differences between groups A and C and between groups B and C in motion range or in the IDP of the adjacent segments when the external force reached the corresponding pressure value (range of motion: 100 N and IDP: 60N) (P<0.05).

The upper adjacent segments had greater range of motion than the lower adjacent segments for anterior flexion, posterior extension, and lateral bending (P<0.05). There were statistically significant differences between the IDP of the upper adjacent segments and the IDP of the lower adjacent segments (P<0.05), indicating that adjacent disc degeneration was more likely to occur at the lower adjacent segments after internal fixation.

Discussion

Main findings and significance

To the best of our knowledge, this is the first study in which goat spine specimens, which are similar in structure to the lumbar spine of the human body, were used to investigate the fixation effects of different segments of the lumbar spine on the adjacent segmental motion and IDP. This study has shown that the motion range and the IDP in adjacent lumbar segments increase with the increase of external mechanical load, but that multisegment fixation of the lumbar spine has more obvious effects on the IDP and motion range of adjacent segments. Moreover, the upper adjacent segment can produce greater motion range under mechanical load, while the effect of external load on IDP is mainly concentrated in the lower adjacent segment.

Lumbar internal fixation is the main method used in treatment of lumbar degenerative disease with instability, and is often combined with lumbar fusion, resulting in an average postoperative clinical satisfaction rate of only 68% [8]. Clinically, rigid internal fixation and high fusion rate do not seem to benefit patients [9–11]. This is mainly due to the development of ASD, which is induced by loss of range of motion of the fixated lumbar segments and compensatory increases in the range of motion and stress on adjacent segments. With the increased number of clinical cases [12] and the long follow-up period, more and more cases of ASD have been reported. The use of biomechanics to study its pathogenesis has become an important focus for researchers [2–4].

The effect of internal fixation on the motion range of adjacent segments

Ignasiak et al. [13] found that stress concentration and loss of physiological motion range after long segmental fixation of the spine resulted in lesions in the proximal junction area and even in kyphosis or failure in the proximal junction area. Based on morphometric analysis, Smit et al. [14] concluded that the goat spinal model is similar to the human spine. Because of the large lumbosacral range of motion in the goat model, the maximum stress is focused on the junction of the movable spine and the fixed pelvis. Li et al. [15] also showed that there was obvious stress concentration in the lower adjacent segment after internal segmental fixation and that the lower adjacent segment was more prone to degeneration and

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caused corresponding symptoms. In this study, the range of motion of adjacent segments after fixation was determined by observing changes in displacement of the lumbar spine in different directions under different mechanical loads. The main results of this study are consistent with the results reported in most previous studies. In motions involving lateral bending, anterior flexion, or posterior extension, the displacement of the upper and lower adjacent segments of the lumbar spine showed an upward trend as the external mechanical load was increased. In particular, the displacement of adjacent segments was more obvious after multiple-segment fixation; this may be related to the effects of mechanical dispersion. In the lumbar spine, the 5 defined motion units have their own motion ranges under physiological conditions. When the lumbar segments are fixed, the fixated segments become a single-motion unit without any internal motion. In this case, when subjected to an external load, the lumbar spine must redistribute the stress. However, as the number of motion units decreases, the amount of stress that is dispersed and transmitted to each motion unit inevitably increases, and the passive range of motion increases accordingly. The more fixated segments there are, the greater is the stress that is exerted on each motion unit and the greater the amount of displacement that occurs in each direction, especially in the case of adjacent upper and lower motion units. The increase in displacement in this study can also be explained by the stress concentration theory [16]; i.e., when a certain segment of the spine is fixated, its own displacement is reduced or eliminated, and the displacement of the fixated segment can only be transmitted to the upper and lower segments. This results in increased displacement, stress concentration, and increased passive motion of these segments.

The effect of internal fixation on the intradiscal pressure of adjacent segments

Adjacent segmental disc degeneration is an important manifestation of ASD, and the increase in IDP is one of the main causes of intervertebral disc degeneration. After multisegment rigid fixation, the IDP in the adjacent segment increases due to the transmission of stress. This accelerates degeneration of the intervertebral disc, resulting in ASD. Zahari et al. [17] found that heavy individuals experience greater IDP in positions of flexion and extension. The persistent increase in pressure compromises the nucleus pulposus of the intervertebral disc more easily than the annulus fibrosus. This is one of the factors that lead to early degeneration of the disc. A cross-sectional study by Hung et al. [18] of 553 patients with intervertebral disc degeneration showed that a high degree of lumbar intervertebral stenosis, a high degree of intervertebral disc dehydration, loss of intervertebral disc height, and lumbar spine degeneration showed a positively correlated dose-response relationship with load accumulation in the lumbar spines of these patients. In addition, the IDP of the adjacent segments increased after fixation [19], and it increased more significantly in patients with long fixated segments [20]. The above findings were confirmed in the studies of Nachemson et al. [21] and in subsequent studies of human IDP measured in a large population [22]. In this study, the IDP of adjacent segments trended upward with the increase in external load and increased in long fixated segments with loads of 60 N and above. This result explains the cause of the degeneration of the intervertebral discs of adjacent lumbar segments after fixation. Metabolic activity and materials exchange in the intervertebral disc depend on the intermittent pressure load. When the pressure is increased, the outflow of water increases and vice versa. Continuous increased pressure affects the water outflow and inflow of the intervertebral disc and causes disorders of material exchange of the intervertebral disc, thereby resulting in disc degeneration [23].

Suggestions based on the results of this study

Lumbar segmental stability is closely related to degeneration, and compromised stability is one of the main factors leading to degeneration. The results of this study suggest that, compared with multisegment fixation, short-segment fixation can significantly reduce the range of motion and the IDP of adjacent segments, and shows that it has the potential to prevent ASD in the long term. Degenerative diseases of the lumbar spine commonly involve multisegment degeneration, and the segments adjacent to the lesion often undergo varying degrees of degeneration [24]. After rigid internal fixation, the altered physiological stress transmission of the human body significantly changes the normal stress transmission of the lumbar spine. Because the fixated segment carries most of the load, the load on this segment is greatly reduced, and a stress-shielding effect occurs. At the same time, the increased stress on and increased range of motion of adjacent segments inevitably aggravate the degeneration of the intervertebral discs and the facet joints of adjacent segments [25]. Based on this, to reduce the incidence of postoperative ASD and to preserve the original physiological range of motion of the lumbar spine as much as possible, we suggest that the number of fixated or fused segments should be minimized when fixation is used to treat lumbar degenerative disease. It is appropriate to fixate the lumbar segments that have poor stability; however, for stable and acceptable segments, simple decompression should be used as a basic standard procedure.

Limitations

This study has certain limitations. First, the isolated goat spine was the subject of this study. However, the physiological curvature of the spine in goats and humans is not identical, and the vertebral bodies and intervertebral spaces are smaller in

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goats than in humans. Although the structural changes that occur in the lumbar spine under mechanical load may be not different, the mechanical load used in this study does not represent the actual load on the human lumbar spine. In addition, human lumbar internal fixation is performed on material with a relatively complete tissue structure. In contrast, in the isolated lumbar spine specimens we selected, the paravertebral muscles had been removed. This not only greatly reduced the mechanical load the specimen was able to bear, but may also have resulted in experimental errors due to damage to the intact structure. Furthermore, due to the limitation of the experimental equipment, it was very difficult to test the ROM of the fixation segment in the actual work. Lastly, variations in individual goats and errors associated with the experimental measurements and data conversion may have affected the results of this study.

Conclusions

The results of our biomechanical experiments showed that fixation of increasing numbers of lumbar segments resulted in progressively greater range of motion and IDP in the adjacent segments. Multisegment fixation is most likely the main factor contributing to ASD after lumbar fusion. The molecular mechanism of ASD after multisegment or long-segment fixation warrants further study.

Conflict of interest

None.

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