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Original paper

Load-bearing evaluation of spinal posterior column by measuring surface strain from lumbar pedicles. An in vitro study

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An understanding of the load transfer within spinal posterior column of lumbar spine is necessary to determine the influence of mechanical factors on potential mechanisms of the motion-sparing implant such as artificial intervertebral disc and the dynamic spine stabilization systems. In this study, a new method has been developed for evaluating the load bearing of spinal posterior column by the surface strain of spinal pedicle response to the loading of spinal segment. Six cadaveric lumbar spine segments were biomechanically evaluated between levels L1 and L5 in intact condition and the strain gauges were pasted to an inferior surface of L2 pedicles. Multidirectional flexibility testing used the Panjabi testing protocol; pure moments for the intact condition with overall spinal motion and unconstrained intact moments of ±8 Nm were used for flexion–extension and lateral bending testing. High correlation coefficient (0.967–0.998) indicated a good agreement between the load of spinal segment and the surface strain of pedicle in all loading directions. Principal compressive strain could be observed in flexion direction and tensile strain in extension direction, respectively. In conclusion, the new method seems to be effective for evaluating posterior spinal column loads using pedicles' surface strain data collected during biomechanical testing of spine segments.

Key words: *surface strain, lumbar pedicle, spinal posterior column, strain gauges, in vitro measurement*

1. Introduction

An understanding of the load transfer within spinal posterior column of lumbar spine is necessary to determine the influence of mechanical factors on potential mechanisms of the motion-sparing implant such as artificial intervertebral disc and the dynamic spine stabilization systems.

In terms of the measurement of posterior column load transmission in experimental spinal biomechanics, many researchers have focused primarily on the contact force and extra-articular strain of facet joint by using surface strain data collected during the biomechanical testing of spine segments, and the accuracy and repeatability of the methods have been validated [1], [15], [17], [19]. However, the results of their studies have shown that facet joint contact forces were variable or inconsistent in flexion (FL), extension (EX), and lateral bending (LB) [19].

Spinal pedicle is not only the key portion to link the anterior and posterior vertebral column in the structure of human spine, but also the important bridge to transfer load between them in terms of function [7], [10]. It has been reported that the tensile and compressive strains at the base of the pedicles in lumbar spine are the highest among all the vertebrae measured by strain gauge methods [8].

It is hypothesized that the strains of pedicles are varied with the load-carrying of posterior column in different motions. Therefore, the objective of the present study was to establish a strain measuring method by using strain gauges on lumbar pedicles and to evaluate its effectiveness in measuring the load-carrying of posterior column during three-dimensional flexibility test in human lumbar spine segments.

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2. Materials and methods

Six fresh-frozen human cadaveric lumbar spines (L1–S1) that came from donor were used in this biomechanical test. The specimens were collected from four males and two females aged between 37 and 65; their height ranged from 157 to 176 cm, and their weight from 55 to 77 kg. Only specimens with no radiographic evidence of bone disease or trauma, or joint degeneration (osteophytes, disc space narrowing or facet hypertrophy) were used in this study. The specimens were kept frozen in double sealed bags at –20 °C. Each specimen was thawed to room temperature in double plastic bag for 4–6 hours and then soaked in normal saline at 37 °C in a plastic bag for 9–12 hours prior to testing. All specimens were kept moist during all the tests by spraying saline. The study was approved by the Office of Research Ethics.

In preparation, the surrounding soft tissue and muscle in lumbar spine were dissected, carefully keeping the intervertebral disc, spinal ligaments and joint capsules intact. The structures in spinal canal and intervertebral foramina were removed and the periosteum of L2 pedicles was resected to allow placement of the strain gauges. In order to fix the specimens in a spine tester, the superior half of L1 vertebra and inferior half of S1 vertebra were embedded in polymethylmethacrylate (PMMA) cement (Shanghai, China). Handling and storage of human cadaver in this way have been routinely practised in in vitro biomechanical investigation, and their influence on the material characteristics of the bone and soft tissues could be ignored [16], [18].

To document the surface strain of pedicle in response to the loading applied to spinal segment, the multidirectional flexibility test was carried out, which involved applying pure moments of FL, EX, and LB in 4 equal steps to a maximum of 8 Nm [6], [14]. The specimens were fixed on the custom-designed spine-testing apparatus in a standing position, which was fixed on a servo-hydraulic material testing machine (MTS 858 bionix machine, MTS Systems Inc., Minneapolis, MU) and allowed the specimens to move in an unrestricted manner [18]. All the specimens were loaded at a room temperature. To generate a pure moment, appropriately equal and opposing forces were applied to the pulleys mounted on top of specimen. Each specimen was applied in three load–unload cycles with an 8 Nm maximum and was allowed to creep for 30 s after each loading-step to minimize viscoelastic effects [11], [18]. On the third load cycle, a measuring series of stepwise progression of the load in each moment followed this protocol: 8 Nm, 6 Nm, 4 Nm, 2 Nm and 0 Nm with 20 s on each step and 10 s transition time between steps. Meanwhile, the outputs of gauges on the specimen were recorded and stored in a computer within 10 s. Prior to recording, the gauges were zeroed with the specimen in an unloading condition.

The components used for strain measurements were assembled and tested before biomechanical testing. The leads of strain gauge (BE120-03AA, Xi'an, Shanxi, China) were soldered to the terminal connected to a cable and a plug, which was linked to an amplifier (Y3825A, Jiangsu, China) that converted the voltage changes in each gauge into units of microstrain (με) and recorded the outputs during the experiment. The resistance (120 Ω) of the gauges was checked to verify electrical continuity before and after a specimen mounting. The surfaces of the lumbar

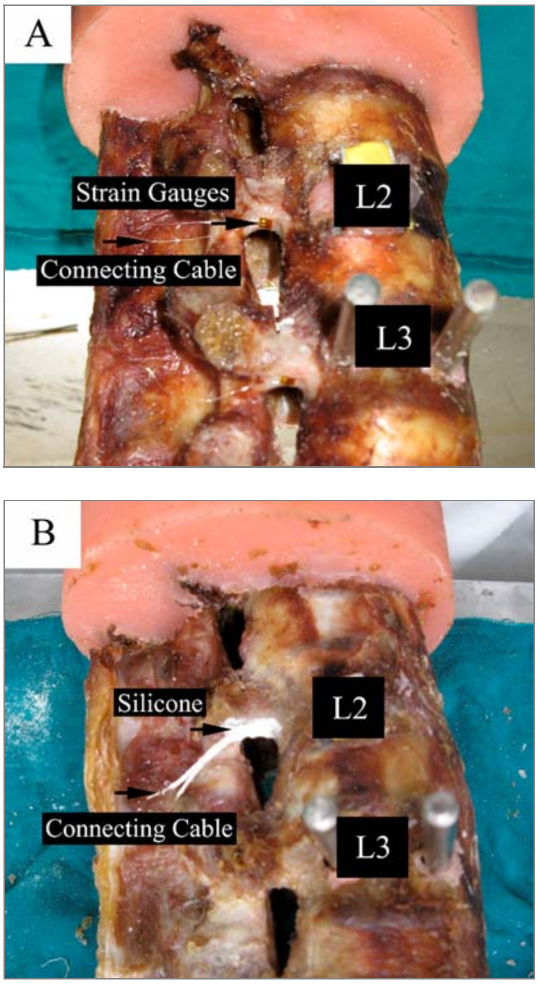

Fig. 1. Strain gauge was pasted to the inferior surface of right pedicle at L2. The gauge unprotected with silicone from moist (A) and the gauge protected with silicone from moist (B). The black arrows point to the strain gauges, connecting cables (A) and silicone (B)

pedicles were cleaned with absolute alcohol and acetone followed by repeated abrading and degreasing with grit emery paper and alcohol. The gauges were glued to the pedicles' surface using a single-component cyanocrylate adhesive (ethyl α-cyanoacrylate, Beijing, China). Two uniaxial strain gauges were bonded to the inferior surface of L2 pedicles, and the longitudinal axis of gauges was parallel to the principal axis of the strain of pedicles [2]. The base-pad of the strain gauges was 2.7 × 2.7 mm, thus it matched with the inferior surface width of L2 pedicles ranging from 4 to 6 mm (figure 1A). Furthermore, each gauge was covered with silicone (Shin-Etsu Silicone, Shin-Etsu Chemical co. Ltd., Chiyoda-ku, Tokyo, Japan) to protect it from moist (figure 1B). Otherwise, a standardized operation was undertaken on the pedicles to make the strain gauges measurement more sensitive: half of the cortex was vertically sawed from the superior side of each measured pedicle.

Data were compiled with the software package SPSS 13.0 (SPSS Inc., Chicago, Illinois, USA). All data were recorded in a Mean ± S.D. way. The linear relationship between strain and loading of pure moment was examined by means of linear regression analysis and correlation was established by computing Pearson's correlation coefficient r square (r^2). The strain of the left and right mean pedicles was analyzed by two-way repeated-measures' analysis of variance (RM-ANOVA) for various loading steps in FL–EX loading direction. Significance was accepted at the $p < 0.05$ level.

3. Results

High correlation coefficient ($r^2 = 0.967–0.998$) indicated a good agreement between the loading of spinal segment and the surface strain of pedicle in all loading directions, as shown in the table. There were significant differences in strain gauge measurements between loading steps in FL ($p < 0.0001$) and EX ($p < 0.0001$). No significant difference in the outputs between both pedicles was found in FL, but a significant difference in strain gauge measurements was observed between both pedicles on the pure moment 2 Nm and 4 Nm of loading steps in EX, the p value was 0.005 and 0.042, respectively (figure 2).

Table. Regression analysis of pure moment and mean strain of pedicles in each loading step

Load direction		Correlation coefficient		Linear regression $y = a + bx$		Standard error (SE) of b	t-statistics (p value)
		r	r^2	a	b		
FL	L*	0.983	0.967	–49.898	–78.059	8.365	–9.332 (0.003)
	R#	0.991	0.982	-87.766	–62.042	4.837	–12.826 (0.001)
EX	L*	0.984	0.969	66.468	94.683	9.809	9.653 (0.002)
	R#	0.998	0.996	–37.398	78.992	3.023	26.131 (0.000)

* The strain gauge mounted on left pedicle of L2. # The strain gauge mounted on right pedicle of L2. FL: flexion, EX: extension.

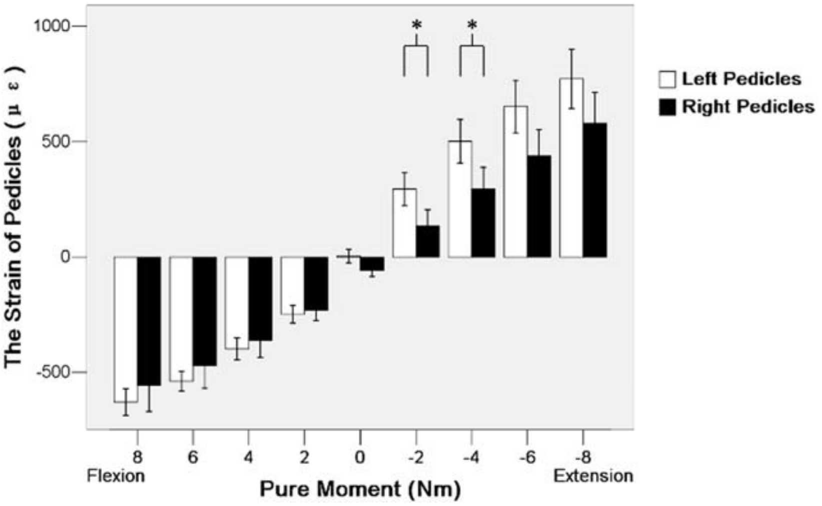

Fig. 2. The strain of the left and right pedicles on each loading step in FL–EX
* Significant difference between left and right pedicles in 2 and 4 Nm in EX, respectively

Principal compressive strain and tensile strain could be observed in FL and EX directions, respectively. In FL, the maximum measured strains of the left pedicle were –630 ± 139.041 με (8 Nm step), and –557.5 ± 277.939 με in the right pedicle (8 Nm). In EX, the maximum measured strains of the left and the right pedicles under 8 Nm loading were 772.33 ± 314.286 με and 580.5 ± 324.616 με, respectively. However, they were variable, and the inconsistency of the direction of principal strain could be observed in LB direction.

4. Discussion

In the study, we bonded strain gauges on the inferior surface of pedicles in lumbar spine to evaluate the use of strain gauge method for the measurement of strain in pedicles, indirectly to evaluate the load bearing of posterior spinal column in in vitro biomechanical testing. The measurements showed excellent linearity between the load and the measured strain for each strain gauge in all loading directions. Significant differences in gauge measurements were found between the loading steps in FL–EX. In addition, there were no significant differences between the left and the right gauge measurements for pedicles in FL. However, the significant difference between the left and the right pedicle gauge measurements were found in 2 and 4 Nm pure moment step in EX (figure 2).

The strain gauge method is recognized to be at present the golden standard in the measurement of surface strain in bone [5]. Furthermore, it was widely used in the lumbar spine biomechanical testing, including vertebral body [8], lateral and medial cortices of lumbar pedicle [9], the superior articular process of zygapophyseal joints [15], the inferior articular process of zygapophyseal joints [19], laminar bone [2], [8], and the pedicle screws' instrumentation [4], [12], [13]. In the biomechanical testing of facet joint, the surface strain data collected was useful and effective in evaluating the contact force of facet joint, furthermore, the accuracy and repeatability of the method have been validated [15], [17], [19]. And the results of these studies showed that facet joint contact force was more repeatable in AR than that in EX, and the facet load patterns were variable or inconsistent in FL, EX and LB. According to the previous studies, the area of cup-shaped articular surfaces being loaded was varied depending on the loading direction of whole specimen [2], [19]. Following the working principle of strain gauge, the outputs of gauges could be very sensitive to induction, while the principal strain of specimen is parallel to longitudinal axis of strain gauge, and that would be the main reason why the measurements of contact force in extra-articular bone surface of facet joint were more repeatable in AR than in EX [3], [7], [17], [19].

The pedicle of vertebral arch links the anterior and posterior columns of spine. It is more important that the principal strain of pedicle is always consistent with the longitudinal axis of pedicle, which indicates that the strain gauge pasted to the pedicle of vertebral arch can successfully be used to evaluate the load bearing of spinal posterior column during biomechanical testing. The repeatability of the method has been proved in this research.

The principal compressive and tensile strains could be observed in FL and EX directions, respectively (figure 2). This proves that the resultant force acts on the spinal posterior column which points at caudal and cephalic directions in FL and EX, respectively. In general, facet joint not only sustains load in EX, but is also shares in shearing force to prevent spondylolisthesis in lower spine segment [10]. Following the results of present research, the elongation of the ligaments of posterior elements avoided excessive spinal FL; furthermore, it played an important role, like facet joint, in preventing spondylolisthesis during FL in lower segments of spine [10]. Furthermore, the reported strain coupling model and coupling motion of lumbar spine could be used to explain the variability of strain value in LB.

The present method has some advantages of evaluating the load of posterior column better than other measuring methods that utilize strain gauge in other position of the vertebral body. The first advantage lies in the fact that the results of this study show that the strains are more repeatable in FL–EX compared with the other methods reported [3], [7], [17], [19]. The second advantage is that this method allows strain gauge to be replaced with other transducer, such as Optical Bragg grating fiber, which was considered to be well suited to in vivo applications [5]. The last important advantage of the method lies in the fact that the compressive and tensile forces of pedicles, which testify to the loading of spinal posterior column bony structure and ligaments, can be measured with only one method.

The results of this study can help us to understand better a biomechanical behaviour of lumbar spine pedicle and loading patterns of posterior spinal column during FL–EX. But there are also some limitations in this study except for some common ones in in vitro biomechanical test. This paper has one limitation: we did not carry out the quantification research based on strain data and the specimen loading during each testing step. The axial compression force was not supplied because it did not affect the accuracy of gauge measurement.

The new solution method appears to be effective in evaluating posterior spinal column loads using pedicle surface strain data collected during the biomechanical testing of spine segments. A further study should be performed to evaluate the relationship between the strain of pedicles and facet joint forces. Based on those studies, the authors are applying the new method to assess the overall load on degenerate segments of posterior spinal column and the adjacent segments of implanted lumbar spine.

Acknowledgements

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