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Lumbar Segmental Motion Properties *In vivo* Determined by a New Intraoperative Measurement System

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Summary. ***In vivo*** **quantitative evaluation of lumbar segmental stability has not been established yet. We developed a new measurement system to determine intraoperative lumbar stability. The purposes of this study were to measure *in vivo* segmental stability and to clarify the relationships between the preoperative radiographic findings and intraoperative measurement parameters. The system consisted of spinous process holders, a motion generator, load cell, optical displacement transducer, and computer. A cyclic displacement (2.0 mm/s, 15 mm max displacement) of the holders produced flexion-extension with all ligamentous structures intact. Intraoperative measurement parameters, including stiffness, neutral zone (NZ), and absorption energy (AE), were determined via load-deformation data. Twenty lumbar segments in 19 patients (M/F=10/9, mean age 59.3 years, range 21-83 years) with degenerative lumbar disease were studied. Range of motion (ROM) and horizontal displacement (HD) were determined from lateral functional X-ray using the method by Dupuis et al. Magnetic resonance images of all discs were categorized into Thompson' s five grades and further into three groups: None (grades 1 and 2, n = 6), Mild (grade 3, n = 10), and Severe (grades 4 and 5, n = 4) degeneration. Relationships between the radiographic findings and the intraoperative measurement parameters were analyzed. In all cases, intraoperative measurement was completed within 10 min without complications. There was no significant relationship between the radiographic findings and intraoperative measurement parameters. Stiffness in the Mild group was significantly lower than that in the other groups (None vs Mild $p < 0.01$, Mild vs Severe $p < 0.05$). The NZ of the Mild group was higher than that in the other groups. AE tended to be lower in the Mild group. Our measurement system established a method to determine stiffness, NZ, and AE by obtaining continuous data *in vivo*. There were no significant relationships between the functional radiographic results and biomechanical data, suggesting that conventional X-ray examinations cannot be used to determine segmental instability. The Mild group had less stiffness and a higher NZ than the other groups, possibly indicating "instability" in patients with mild disc degeneration.**

Key words — intraoperative measurement, segmental instability, lumbar spine, stiffness, neutral zone, absorption energy.

INTRODUCTION

Lumbar segmental motion properties are investigated using various methods. Biomechanical studies provide information on basic motion properties *in vitro*[1,2,3] whereas radiography is used for *in vivo* studies [4,5]. X-rays, including functional radiograms, are conventionally used to examine lumbar motion. The advantages of X-rays are that no special equipment is needed, and they are inexpensive and easy to perform.

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Abbreviations– AE, absorption energy; CV, coefficient of variation; HD, horizontal displacement; NZ, neutral zone; ROM, range of motion.

X-rays, however, only reveal the maximum positions of extension, and flexion of the lumbar spine demonstrates a temporary position of the spine but not its dynamic motion.

Intraoperative measurements are used to determine dynamic motion properties of an actual lumbar segment. Ebara et al.[6] developed a manual spinal spreader, suspended between two adjacent spinous processes, for measuring the tensile stiffness of spinal motion segments. They investigated the relationship between segmental stiffness, and disc degeneration or graded decompression, and fusion surgeries. Brown et al.[7] further developed a spinal spreader using a computerized system and concluded that the device was effective for providing an objective, quantitative, intraoperative measurement of stiffness of the lumbar spine segment. In both studies, however, the motion segment stiffness alone was measured under non-physiologic conditions in which the posterior elements (e.g. supra- and inter-spinous ligament) were removed. From a biomechanical viewpoint, segmental properties of the spinal segment cannot be determined only by stiffness; other parameters, such as a neutral zone (NZ), are necessary[8].

Since 1997, we have been developing a new intraoperative measurement system through *ex vivo* studies[9] to measure real spinal motion properties with detailed biomechanical data and with sufficient intraoperative safety. The purposes of this study were to measure lumbar segmental motion properties with the new device and to clarify the relationship between radiographic mobility using functional X-rays or disc degeneration using magnetic resonance imaging (MRI) and biomechanical properties determined by the intraoperative measurement.

METHODS

An original device for intraoperatively measure lumbar segmental motion

The device consisted of novel spinous process holders (Gi-5, Mizuhoikakikai, Niigata), a flexion-extension motion generator (RC-RSW-L-50-S, IAI Corporation, Shimizu, Shizuoka), and a personal computer (Fig. 1). The two holders firmly gripped adjacent spinous processes (Fig. 2). Cyclic caudocephalic displacement at a speed of 2.0 mm/s was generated to the tip of the holders with a maximum displacement of 15.0 mm from the neutral position. The neutral position was defined as the position in which there was no load

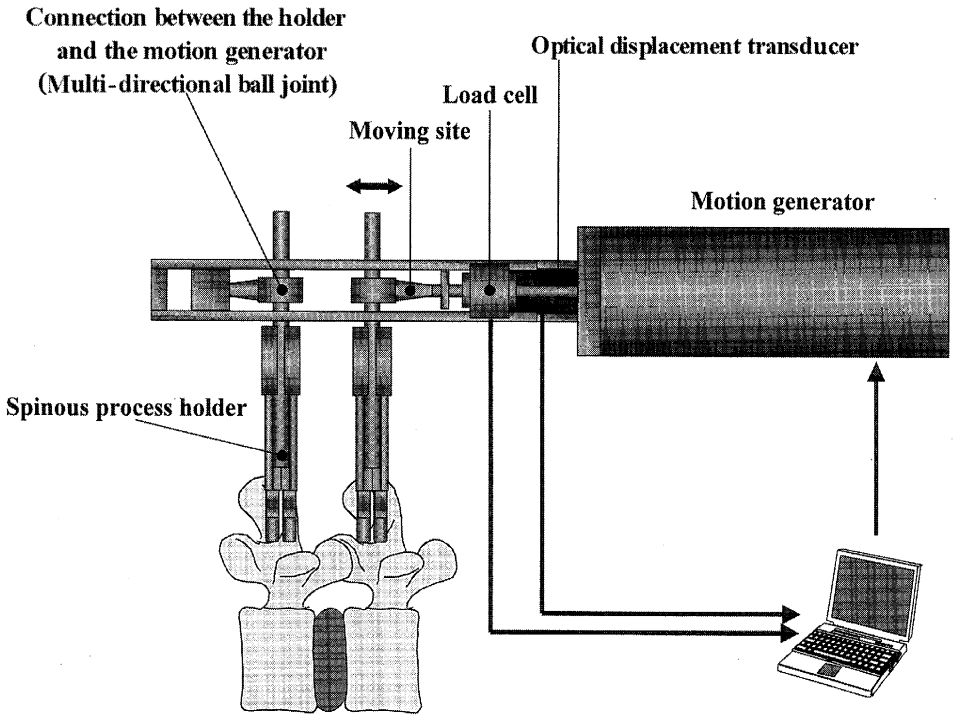


Fig. 1. A new intraoperative measurement system for lumbar segmental motion properties. A caudal spinous process holder is moved with a motion generator, load is measured with a load cell, and displacement is measured using an optical displacement transducer.

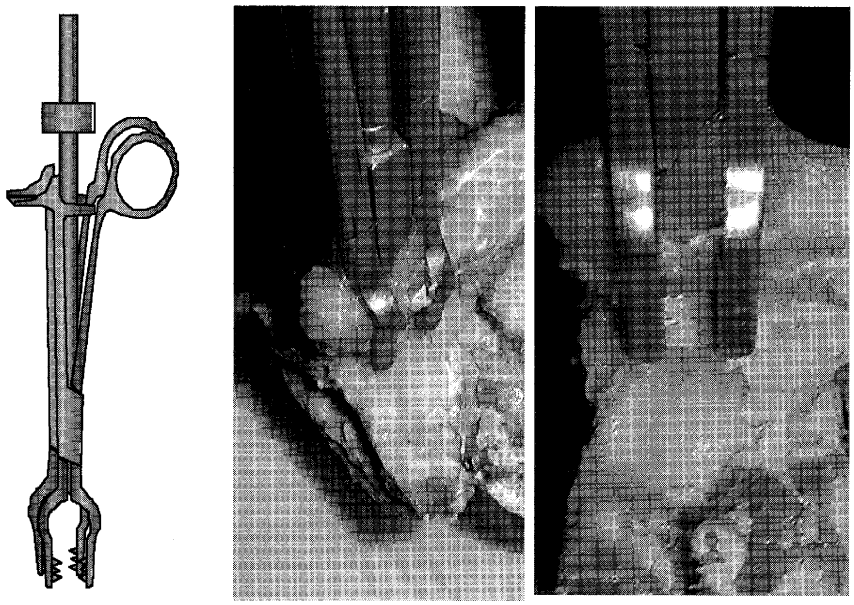


Fig. 2a. Scheme of an original spinous holder. The holding site had three sets of spikes. **b.** and **c.** The holder firmly grips the spinous processes.

at the motion segment. Load at the tip of the caudal spinous process holders was measured with a load cell (LUR-A-200NSAI, Kyowadengyo Corporation, Chofu, Tokyo) and displacement was measured using an optical displacement transducer (LB-080, Keyence, Chofu, Tokyo). Real-time load-displacement data were obtained via a personal computer. The spinous process holder was connected to the motion generator through a multi-directional ball joint, producing flexion-extension from a caudocephalad motion.

Experimental procedure

This study was initiated following the approval of the Committee of Medical Ethics of Niigata University (approval # 182, 2003). Informed consent was obtained from all patients who were examined in this series. Segmental motion measurement was performed in either the scheduled segment or the adjacent segment. The patient was placed in the prone position on a Hall's frame and paraspinal muscles were detached from the spinous processes using standard procedures. Two holders were attached to the adjacent spinous processes. All ligamentous structures of the functional spinal unit including supra- and inter-spinous ligaments and facet joints were preserved intact. The motion generator attached to the tip of the holders loaded the segment, producing three flexion-extension segmental motion cycles, and real-time load-displacement data were obtained with a sampling rate of 200 ms. The third data cycle was used for biomechanical analysis of the viscoelastic properties of the spine.

Patients and preoperative image analyses

Twenty spinal motion segments in 19 patients (men, n = 10; women, n = 9; mean age 59.3 years, range 21-83 years) with degenerative lumbar disease were enrolled in the study. The diagnoses were degenerative spondylosis (n = 7), lumbar canal stenosis (n = 7), and discopathy (n = 6).

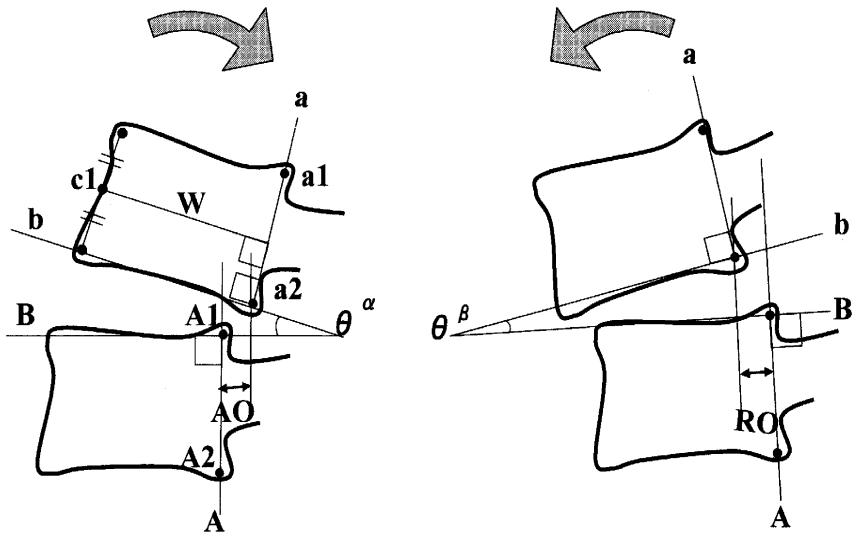
Lateral X-rays were taken under the following conditions: lines between the bilateral acromion processes and iliac crests were placed perpendicular to X-ray films, the distance from the X-ray generator to the film was 2.5 m, and the voltage/electric currents of the X-ray generator were 110 kV / 140 mA. First, an X-ray was taken in the neutral standing position, then in the maximum forward flexed lateral position, and finally in the maximum backward flexed lateral position. The preoperative lumbar X-rays were scanned and saved in a personal computer as digitized images. The origin

was located at the left-upper corner of each scanned image. The X-axis was placed along the horizontal line of the scanned image and the Y-axis was rendered perpendicular to the X-axis. On a scanned functional X-ray of the extension position, points a1 and a2 were defined as the posterior-superior and posterior-inferior corners of the adjacent upper vertebra at each measured spinal segment. Points A1 and A2 were also defined as the posterior-superior and posterior-inferior corners of the adjacent lower vertebra. C1 was defined as the middle point of the line between the anterior-superior and anterior-inferior corners of the adjacent upper vertebra (Fig. 3). X and Y coordinates of all points were measured with image analysis software (Scion image alpha 4.0.3.2). θ^{α} was defined as the angle between line a (line a1-a2) and line A (line A1-A2). AO was defined as the distance between point a2 and line A. W was defined as the distance between point C1 and Line a. In the same manner, θ^{β} and RO were defined on a scanned functional X-ray of the flexion position. θ^{α}, θ^{β}, AO, RO, and W were calculated in all preoperative X-rays, and then range of motion (ROM) and horizontal displacement (HD) were measured using the method by Dupuis et al.. (Fig. 3)

MRI with a 1.5T magnetic resonance imager was taken in all patients. Two experienced orthopaedic surgeons analyzed all MRI images independently. They differentiated five grades of disc degeneration according to the classification system proposed by Pearce[10]. In a final readout, a consensus decision of each disc grade was reached in conference. Finally, grades 1 and 2 were defined as None, 3 as Mild, and 4 and 5 as Severe. (Table 1)

Data analysis

A characteristic load displacement curve was obtained and we defined three motion parameters to describe the spinal motion properties: stiffness, neutral zone (NZ), and absorption energy (AE). (Fig. 4) Stiffness (N/mm) was defined as the slope of the line fitting the load-displacement curve from −15 mm to −10 mm on flexion motion. The NZ (mm) was measured fitting a straight line to the load-displacement curve from −5 mm to 5 mm. The NZ was defined as the distance



Range of motion (ROM) = $\theta^{\alpha} + \theta^{\beta}$

Horizontal displacement (HD) = {(AO + RO)/W} × 100

Fig. 3. Methods of measuring range of motion (ROM) and horizontal displacement (HD).

Table 1. Grading system proposed by Pearce

Disc grade	Structure	Distribution of nucleus and anulus	Signal intensity	Height of intervertebral disc	Level of severity
I	Homogeneous, bright white	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal	None
II	Inhomogeneous with or without horizontal bands	Clear	Hyperintense, isointense to cerebrospinal fluid	Normal	
III	Inhomogeneous, gray	Unclear	Intermediate	Normal to slightly decreased	Moderate
IV	Inhomogeneous, gray to black	Lost	Intermediate to hypointense	Normal to moderately decreased	Severe
V	Inhomogeneous, black	Lost	Hypointense	Collapsed disc space	

We divided these grades into three level of severity; None (grades 1 and 2), Mild (grade 3), Severe (grades 4 and 5).

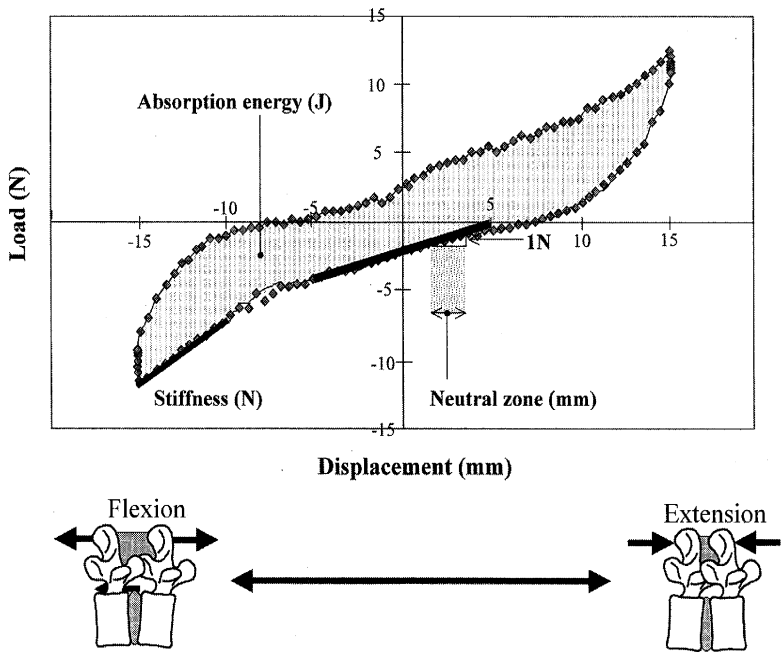


Fig. 4. A typical hysteresis curve generated through intraoperative measurement. Stiffness (N/mm) was defined as the slope of the line fitting the load-displacement curve from −15 mm to −10 mm on flexion motion. The neutral zone (NZ) (mm) was measured fitting a straight line to the load-displacement curve from −5 mm to 5 mm. The NZ was defined as the distance along this line required to produce a load of 1N. Absorption energy (AE) (J) was defined as the area of the obtained hysteresis loop.

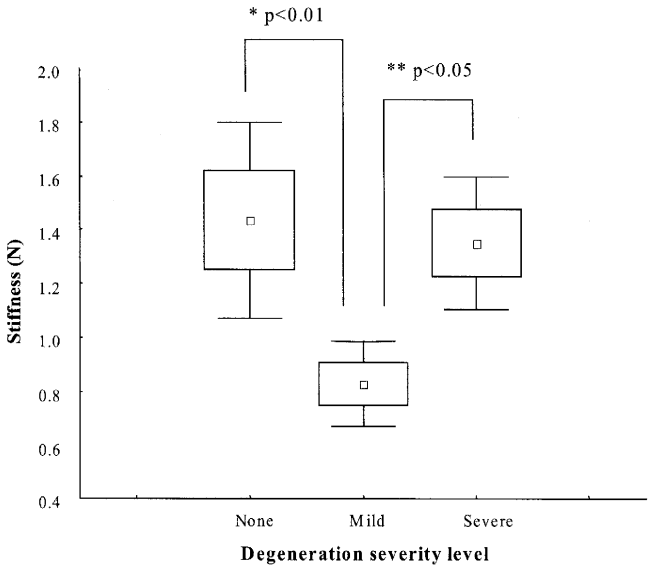


Fig. 5. Data of median stiffness obtained with the intraoperative measurement system. Stiffness of spinal segments in the Mild group was significantly lower than those in the other groups (None vs Mild $p < 0.01$, Mild vs Severe $p < 0.05$). There was no significant difference in stiffness between the None and Severe groups ($p = 0.922$).

along this line required to produce a load of 1N. All the lines used for measuring stiffness and the NZ were calculated using the least-squares method. AE (J) was defined as the area of the obtained hysteresis loop[11,12]. Preliminary examination of a porcine lumbar spine was performed and the reproducibility of each parameter was determined. Coefficient of variation (CV = standard deviation / mean * 100) of each parameter was as follows: Stiffness (8%), NZ (8%), and AE (11%)[13].

Statistical analyses were performed using STATISTICA statistical software version 6.1 (StatSoft, Oklahoma, USA). Pearson's product moment method was performed for correlation analysis among functional radiographic parameters, intraoperative measurement parameters, and between both of these. The clinical level of significance was 0.05. Analysis of each intraoperative measurement parameter was performed as follows. After Levene's test for equality of variances, a one-way analysis of variance (ANOVA) was performed across the three disc degeneration levels. The clinical level of significance was 0.05. If the one-way ANOVA results indicated a difference between the groups, the Scheffe method was used for multiple comparisons.

RESULTS

Radiographic and MRI results

The mean ± standard deviation of ROM was 7.16 ± 4.94 degrees. The maximum and minimum values were 22.74 and 1.09 degrees, respectively. The mean ± standard deviation of HD was 3.61 ± 2.68 mm. The maximum and minimum values were 8.38 and 0.68 mm, respectively. The incidence of disc degeneration grades in MRI assessed by each reader were summarized, and the consensus reading resulted in 4 grade - 1 discs, 2 grade - 2 discs, 10 grade - 3 discs, 2 grade - 4 discs, and 2 grade - 5 discs. We divided these grades into three levels of severity: None (n = 6), Mild (n = 10), and Severe. (n = 4)

Intraoperative segmental motion parameters

The mean ± standard deviation of stiffness was 1.11 ± 0.43 N, ranging 1.80 to 0.47 N. The mean ± standard deviation of the NZ was 1.42 ± 0.60, ranging 3.15 to 0.83 mm. The mean ± standard deviation of AE was 0.26 ± 0.09 J, ranging 0.46 to 0.13 J.

Statistical results

There was a significant relationship between range of motion (ROM) and HD ($R = 0.70$, $p = 0.0006$). There were significant relationships between stiffness and the NZ ($R = -0.53$, $p = 0.016$), NZ and AE ($R = -0.60$, $p = 0.005$), and stiffness and AE ($R = 0.46$, $p = 0.04$). There were no significant relationships between functional radiographic parameters and biomechanical parameters (ROM vs stiffness $R = 0.36$, $p = 0.12$; ROM vs NZ $R = -0.14$, $p = 0.56$; ROM vs AE $R = -0.01$, $p = 0.74$; HD vs stiffness $R = 0.06$, $p = 0.81$; HD vs NZ $R = 0.22$, $p = 0.35$; HD vs AE $R = -0.31$, $p = 0.18$).

The mean and standard deviation of stiffness in the None, Mild, and Severe groups are shown in Fig.5. Stiffness of spinal segments in the Mild group was significantly lower than in the other groups (None vs Mild $p = 0.008$, Mild vs Severe $p = 0.046$). There was no significant difference in stiffness between the None and Severe groups ($p = 0.922$). The mean and standard deviation of the NZ and AE are shown in Fig.6. NZ in the Mild group was higher than in the other groups, but there were no significant differences between disc degeneration levels (None vs Mild $p = 0.53$, Mild vs Severe $p = 0.98$, None vs Severe $p = 0.77$). The Severe group had the highest AE, but there were no significant differences between disc degeneration levels (None vs Mild $p = 0.81$, Mild vs Severe $p = 0.27$, None vs Severe $p = 0.61$).

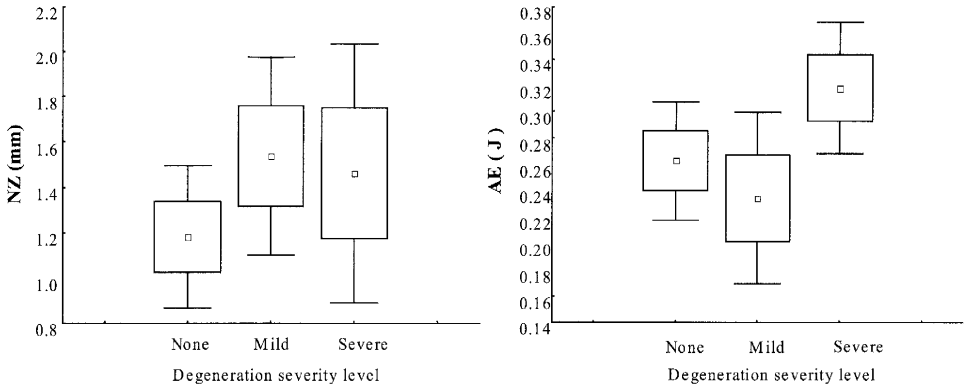


Fig. 6. Data of median NZ and AE. The NZ in the Mild group was higher than that in the other groups, but there were no significant differences between disc degeneration levels (None vs Mild p = 0.53, Mild vs Severe p = 0.98, None vs Severe p = 0.77). The Severe group had the highest AE, but there were no significant differences between disc degeneration levels (None vs Mild p = 0.81, Mild vs Severe p = 0.27, None vs Severe p = 0.61).

DISCUSSION

Our measurement system was established as an *in vivo* method to determine stiffness, NZ, and AE using continuous data. There are no reports of a system that enables the analysis of lumbar motion properties with all ligamentous structures intact. Importantly, the measurements were performed in a safe manner, and there were no injurious events such as fracture, ligament rupture, or nerve injury during any of our intraoperative measurements.

There were no significant relationships between the functional radiographic parameters and intraoperative measurement parameters. Previous studies did not suggest significant relationships between the results of functional radiographs and intraoperative measurements[6,7]. In fact, it seems reasonable that there is no relationship between these parameters. When regional ROM and HD are considered, the maximum flexion and extension positions are based on the patient's ability. There might be some limitation due to the severity of back pain and the influences of individual muscle power variance. ROM and horizontal diplacement (HD) measured by functional radiograms represent the angle and distance during the state of maximum flexion and extension, but the power or torque exerted on the segment is unclear. The results of the present study suggest that conventional X-ray examinations cannot be used to determine intraoperative segmental instability.

There was a non-linear relationship between measured segmental stiffness and disc degeneration severity. In the early stage of disc degeneration, segmental stiffness significantly decreased as the grade progressed from none to mild. The stiffness, however, increased as disc degeneration progressed from mild to severe. These findings are consistent with previous reports of intraoperative measurements[7]; they possibly support the concept of three stages of spinal degeneration proposed by Kirkaldy-Willis[14].

It has been proposed that the NZ is most affected by degeneration and that this can lead to painful motion[8]. To our knowledge, there are no reports of investigations in which the NZ was used as an intraoperative motion parameter. An *in vitro* study with fresh human cadavers reported that the NZ increased slightly with greater disc degeneration in lumbar flexion-extension motion[3]. In the present study, the NZ tended to increase when the initial stage of disc degeneration increased from none to mild. The NZ, however, did not increase as disc degeneration progressed further, suggesting that disc degeneration processes during the progression from mild to severe produce stability[14].

Few reports discuss the relationship between disc degeneration and AE or hysteresis. A study of human cadavers indicated that hysteresis varies with age, is large in young people, but decreases in the middle decades of life[11]. In that report, however, the actual variance of hysteresis and changes with disc degeneration were not reported. An *in vitro* study clarified that experimental disc injury reduced the hysteresis in flexion and extension spinal motion[15]. We concluded that the reduced hysteresis could be explained by two factors: the peak moment reduction produced by injury, and the net energy loss from

the annular disc fibers reduced by the injury. In the present study, AE decreased in the early stage of disc degeneration (None to Mild) and increased in the later stage (Mild to Severe). In particular, AE was highest in the severe stage of disc degeneration. AE might be reduced by an annular tear in the mild disc degeneration stage. In the severe disc degeneration stage, hypertrophy of degenerated soft tissue (i.e., facet joint capsule, ligamentum flavum, and calcified disc annulus) and hypomobility of ankylosed facet joints might contribute to increased AE.

This study has some limitations. The number of specimens was not large enough for a complete statistical analysis of the probable differences among disc degeneration levels. Further, the spinal level difference for each spinal motion segment was not investigated in this study. Another major limitation was the lack of standardization of individual differences. Since almost all intraoperative measurement was performed on a spinal motion segment in a patient, there were individual differences among the measurements.

One study of intraoperative measurements reported that stiffness measurements did not correlate with the clinical results of surgery[16]. The study only evaluated segmental stiffness and possibly missed a real "segmental instability", which should be clarified using multiple biomechanical parameters including the NZ. We believe that with the use of our intraoperative measurement system "segmental instability" can be determined using stiffness, NZ, and AE as parameters. Therefore, further accumulation of clinical data on segmental properties using this system should contribute to determine the indication for lumbar fusion surgeries.

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