Specific Aims
The specific aim of this study is to correlate the biomechanical characteristics of lumbar motion segments with the morphological appearance of the intervertebral disc, vertebral body, and facet joint by:

(1) Determining the stability of the motion segment by measuring the segmental stiffness in flexion, extension, lateral bending, and axial rotation,

(2) Determining the pathoanatomical changes before and after loading (i.e., foraminal area, nerve root impingement, disc bulging, facet subluxation, etc) using MRI and the cryomicrotomic techniques,

(3) Investigating MRI characteristics of the lumbar intervertebral disc and adjacent marrow to quantify the grades of disc degeneration and Modic types of disc degeneration, and

(4) Investigate possible correlations between above findings.

Introduction: Spinal degeneration includes the osteoarthritic changes of the facet joint as well as disc degeneration. Disc degeneration has been reported to be associated with spinal motion. The association of facet joint osteoarthritis with lumbar segmental motion characteristics and the combined influence of disc degeneration and facet osteoarthritis has not yet been investigated. Morphologic changes in the intervertebral foramen during flexion and extension as well as lateral bending and axial rotation are not well known, and dynamic stenosis frequently gives symptoms that are not readily diagnosed on static imaging studies. MRI is a powerful tool to investigate the morphologic changes in the lumbar spine, and correlating between MRI findings such as HIZ (high intensity zone) and Modic endplate changes with kinematics will give further insights into these MRI findings.

Effect of disc degeneration on lumbar stiffness. Lumbar motion segments (52 female, 58 male) from human lumbar spines were studied (mean age = 69 years). Magnetic resonance images were used to assess the disc degeneration from Grade I (normal) to Grade V (advanced) and the osteoarthritic changes in the facet joints in terms of cartilage degeneration, subchondral sclerosis, and osteophytes. Disc height, endplate size, and facet joint orientation and width also were measured from the computed tomographic images. Rotational movements of the motion segment in response to the flexion, extension, lateral bending, and axial rotational moments were measured using a three-dimensional motion analysis system. Female motion segments showed significantly greater motion (lateral bending: \( P < 0.001 \), flexion: \( P < 0.01 \), extension: \( P < 0.05 \)) and smaller endplate size (\( P < 0.001 \)) than male ones. The segmental motion increased with increasing severity of disc degeneration up to Grade IV, but decreased in both genders when the disc degeneration advanced to Grade V. In male segments, the disc degeneration-related motion changes were significant in axial rotation (\( P < 0.001 \)), lateral bending (\( P < 0.05 \)), and flexion (\( P < 0.05 \)), whereas female segments showed significant changes only in axial rotation (\( P < 0.001 \)). With cartilage degeneration of the facet joints, the axial rotational motion increased, whereas the lateral bending and flexion motion decreased in female segments. In male segments, however, motion in all
directions increased with Grade 3 cartilage degeneration and decreased with Grade 4 cartilage degeneration. Subchondral sclerosis significantly decreased the motion (female: axial rotation, \( P < 0.05 \); extension, \( P < 0.05 \) vs.— male: flexion, \( P < 0.05 \)). Severity of osteophytes had no significant association with the segmental motion. Axial rotational motion was most affected by disc degeneration, and the effects of disc degeneration on the motion were similar between genders. Facet joint osteoarthritis also affected segmental motion, and the influence differed for male and female spines. Further studies are needed to clarify whether the degenerative process of facet joint osteoarthritis differs between genders and how facet joint osteoarthritis affects the stability of the spinal motion segment.

**Effect of motion on morphologic changes in the intervertebral foramen:** The morphologic changes in the intervertebral foramen during flexion, extension, lateral bending, and axial rotation of the lumbar spine were examined and were correlated with the flexibility of the spinal motion segments. Human cadaveric lumbar spines (mean age 69 years) were used to obtain the motion segments and imaged with CT scanner with 1-mm thick consecutive sections. For biomechanical testing each motion segment was applied with incremental pure moments of flexion, extension, lateral bending, and axial rotation. Rotational movements of the motion segment were measured using VICON cameras. After application of the last load, the specimens were frozen under load, and then CT was performed with the same technique described above. Six parameters of the intervertebral foramen were measured, including foraminal width (maximum and minimum), foraminal height, disc bulging, thickness of ligamentum flavum, and cross-sectional area of the foramen. Flexion increased the foraminal width (maximum and minimum), height, and area significantly while significantly decreasing the disc bulging and thickness of ligamentum flavum (\( P < 0.05 \)). However, extension decreased the foraminal width (minimum), height, and area significantly. Lateral bending significantly decreased the foraminal width (maximum and minimum), height, and area at the bending side, whereas lateral bending significantly increased the foraminal width (minimum), height, and area at the opposite side of bending. Likewise, axial rotation decreased the foraminal width (minimum) and area at the rotation side significantly while significantly increasing the foraminal height and foraminal area at the opposite side. The percent change in the foraminal area was found significantly correlated with the amount of segmental spinal motion except for the extension motion. This study showed that the intervertebral foramen of the lumbar spine changed significantly not only on flexion–extension but also on lateral bending and axial rotation. The percent change in cross-sectional foraminal area was correlated with the amount of segmental motion except for extension motions. Further studies are needed to assess the morphologic changes in the intervertebral foramen in vivo and to correlate clinically.

**Effect of HIZ on lumbar motion segment stiffness:** Human cadaveric lumbar spinal motion segments with normal disc morphology or a high-intensity zone of the anulus fibrosus were selected on the basis of magnetic resonance imaging. The motion segments were subjected to incremental flexion, extension, rotation, and lateral bending torques. Rotation was measured with a kinematic system. Torque-rotation curves and stiffness were calculated for each motion segment and for each torque. The motion segments were sectioned on a cryomicrotome to verify the disc morphology as normal or as that of a radial tear. In four motion segments with normal discs, stiffness was greater in axial rotation (8.4 Nm/°) than in lateral bending (2.3 Nm/°), flexion (1.8 Nm/°), or extension (2.6 Nm/°). In 16 motion segments with a high-intensity zone, stiffness was 2.4 Nm/° in axial rotation, and less severely reduced in lateral bending, flexion, and extension.
Stiffness in motion segments with a high-intensity zone was significantly less with smaller than with larger axial rotation loads. The presence of a high-intensity zone in the intervertebral disc is associated with reduced stiffness of motion segments. The reduction is greater in axial rotation than in other torques. The reduction is more in smaller than in larger axial torques.