INTRODUCTION: Spondylolisthesis is defined as a forward slippage of a vertebral body on the one below. Isthmic spondylolisthesis, caused by stress fracture or a developmental anomaly at the pars interarticularis, is the most common type of lumbar spondylolisthesis with a 6% incidence in adults. Progressive spondylolisthesis may occur in adults, and is a frequent cause of disabling low-back and leg pain. Clinical studies suggest that disc degeneration at the slip level may be a contributing factor to converting a stable spondylolisthesis into unstable progressive slip (1).

To date, a laboratory model of adult-onset slip progression in isthmic spondylolisthesis does not exist. Previous biomechanical studies (2,3) showed that bilateral pars disruption alone failed to produce anterior slip at the affected segment. The role of the iliolumbar ligament in preventing the progression of L5 slip remains unclear.

This study tested the hypothesis that anterior slip progression of L5 on sacrum in adult spines with bilateral pars fracture at L5 is predicted by (i) the extent of load-bearing deficiency of the disc, and (ii) the magnitude of shear/compression force ratio at the L5-S1 segment. The hypothesis was tested using adult lumbar spine specimens with bilateral L5 pars fractures to identify the critical combinations of disc mechanical deficiencies and loading conditions that can cause progression of slip at L5-S1.

METHODS: Each lumbar spine specimen (L1-sacrum) was positioned in the loading apparatus using video fluoroscopy such that the superior endplate of sacrum was inclined at a 45-degree angle from horizontal. The specimen was subjected to physiologic compressive loads of up to 1200 N. The compressive load was applied bilaterally via loading cables along the lordotic curve of the lumbar spine (follower load path), thereby subjecting each normal segment to nearly pure compressive load perpendicular to the disc endplate (Fig. 1a) (4). We simulated two values of the shear/compressive force ratio (0 and 1) at L5-S1 by altering the path of the loading cables across the L5-S1 segment. When the cable path was vertical across the L5-S1 disc space (Fig. 1b), the segment was subjected to combined shear force (parallel to the disc endplate) and compression (perpendicular to the endplate). The shear/compression force ratio in the case of vertical loading was 1.0 due to the horizontal sacral angle of 45 degrees. The ratio of shear to compression was zero for the follower load condition (pure compression across L5-S1) (Fig. 1a).

Performing a partial nucleotomy simulated the load-bearing deficiency (decreased resistance to load) of a degenerated L5-S1 disc. A small incision was made in the posterosuperior annulus and a portion of the nucleus (4-5 g) was removed. The annular incision was then sutured. A separate study (5) showed this procedure decreased the compressive and shear stiffness of the disc, simulating the biomechanical behavior of a moderately degenerated disc.

The lumbar spine specimens were tested in the following sequence: (i) intact, (ii) after creating bilateral pars fracture at L5 using an oscillating saw, and (iii) after partial nucleotomy at L5-S1. In each specimen condition, the specimens were subjected to two loading paths across L5-S1 (follower load path, vertical load path), simulating two values of the shear/compression force ratio. For a given loading path, the response of the specimen was measured for gradually increasing load from 0-1200 N applied in the neutral posture, simulating in vivo compressive load on a patient’s lumbar spine while standing. We also measured the flexion-extension range of motion of the L5-S1 segment under no preload for the intact spine, after creating bilateral pars fractures at L5, and after partial nucleotomy at L5-S1. This allowed us to compare our results to previous studies. The motion of L5 over sacrum was monitored using (i) an optoelectronic motion analysis system, and (ii) video fluoroscopy giving dynamic radiographic images of the L5-S1 segment. The angular motion and translation (slip) of L5 over sacrum were compared among the different tested cases.

RESULTS: The bilateral pars fractures at L5 caused an increase in L5-S1 flexion-extension range of motion (ROM) by 27% (s.d. 7.5). Under the flexion-extension moments, the L5 pars fractures did not yield any measurable translation of L5 on sacrum.

The amount of nucleus material removed during the partial nucleation procedure averaged 4.6 gm (s.d. 0.78), which represented on average 61% (s.d. 7.5) nucleus removal. The partial nucleotomy procedure reduced the compressive and shear stiffness of the L5-S1 disc by 65% (+23) and 44% (+15), respectively (5). After a partial disc denucleation, the flexion-extension ROM increased by 57% (s.d. 2.8) relative to intact. However, the flexion-extension moments did not yield any measurable spondylolytic deformity even after partial disc denucleation.

As increasing load (0-1200 N) was applied in the upright posture along the follower load path across the L5-S1 segment (shear/compression force ratio=0), the anterior translation of L5 on sacrum did not increase after bilateral pars fractures at L5 nor after partial disc denucleation (Fig. 2a). A significant translational motion of L5 on sacrum was noted after the partial nucleotomy under an increasing load applied in the upright posture with a shear/compression force ratio of about 1.0 across L5-S1. At 1200 N load, the anterior slip of L5 averaged 24% (s.d. 9.1) of A-P vertebral body width (Fig. 2b). When the load was removed, the residual translational deformity measured 17% (s.d. 9.1).

Table 1. Slip outcome under 1200 N load for different test conditions.

<table>
<thead>
<tr>
<th>Specimen Condition</th>
<th>Shear/Compression=0</th>
<th>Shear/Compression=1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pars Fx Alone</td>
<td>No Slip</td>
<td>No Slip</td>
</tr>
<tr>
<td>Pars Fx+Intact Disc</td>
<td>No Slip</td>
<td>No Slip</td>
</tr>
<tr>
<td>Pars Fx+“Degen” Disc</td>
<td>No Slip</td>
<td>Grade 2 Slip</td>
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</table>

DISCUSSION: Our results showed that while bilateral pars disruption alone caused increased angular motions, it failed to produce anterior slip at the affected segment. This is consistent with previous studies (2,3). The lack of increase in forward translation following pars disruption suggests that division of the pars interarticularis alone is not likely to produce spondylolisthesis.

In adult spines with bilateral L5 pars fractures, an anterior slip of L5 depends on the extent of the load-bearing deficiency of the disc and the shear/compressive force ratio across L5-S1. Disc degeneration at the slip level may be a factor in converting a stable spondylolisthesis into unstable progressive slip. As the disc degenerates, its capacity to resist the anterior shear forces is considerably diminished, leading to further subluxation. Our findings are consistent with the clinical observations that patients with an underlying spondylolytic defect remain asymptomatic for many years until disc degeneration adversely affects the stability of the lumbosacral segment, leading to a progression of the slip (1). Further studies are needed to develop a predictive model of adult-onset slip progression to help target preventive modalities such as physical therapy to patients who are at risk to progress.