Pedicle Screw Trajectory and Cage Use Influence L5–S1 Fusion Stability in Spondylolysis and Spondylolisthesis

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INTRODUCTION: Lumbosacral spondylolysis and spondylolisthesis are leading causes of low back pain in pediatric and young adult patients; particularly adolescent athletes engaged in repetitive hyperextension sports. When symptoms persist or vertebral slippage progresses, an L5-S1 fusion is often indicated; however, this level is biomechanically challenging and carries a high risk of hardware failure due to the steep screw trajectories and complex lumbosacral loads. Current surgical strategies vary widely, including differences in pedicle screw trajectory (straight versus angled) and the use of interbody cages for anterior support, but comparative biomechanical data in younger patients are limited. This study was designed to address these gaps by comparing (1) spondylolysis versus spondylolisthesis models, (2) 12° versus 30° screw trajectories, and (3) the effect of interbody cage use on construct stability in L5-S1 fusion. We hypothesized that straighter screw trajectories, combined with interbody cage support, would improve biomechanical stability and reduce hardware failure, as measured by stiffness, displacement, and micromotion under simulated loading.

METHODS: This biomechanical comparison study utilized synthetic L4–S1 spine models (N = 20) representing spondylolysis and spondylolisthesis (Grade II, per Meyerding classification) to simulate pediatric L5–S1 fusion constructs under physiologic loading. Each model underwent pedicle screw instrumentation at L5 with either straight (12°) or angled (30°) screw trajectories (**Fig 1A**). A subset of patients received interbody cages after completing the first round of tests. All constructs underwent flexion-extension loading on a custom hinge-based fixture using a biaxial Instron machine, with incremental torques (1, 2, 4, and 6 Nm) applied under a 400 N preload. A subset also underwent side bending and destructive testing to evaluate failure thresholds. Instrumentation was performed with robotic assistance for precision screw placement at 15–20° angles. Specimens were instrumented using standard clinical technique, including pre-drilling, tapping, and rod placement. Strain, displacement, and micromotion were measured using 3D Digital Image Correlation (DIC), a non-contact, high-resolution imaging system. Each construct was tested through 20 loading cycles, and pilot testing was conducted to optimize the protocol prior to full data collection. A subset of samples underwent destructive testing to determine failure load **(Fig 1B)**.

RESULTS SECTION: Initial data suggest increased motion and micromotion at higher torque levels in both sagittal (Y-axis) during flexion and coronal (Z-axis) during side bending. The addition of interbody cages reduced flexion displacement in most cases and appeared to enhance construct stiffness. Side-bending results were consistent with flexion-extension trends. In the comparison of spondylolysis vs. spondylolisthesis, both groups showed increased displacement with force; while the spondylolysis group exhibited higher values overall, the difference was not statistically significant. Similarly, in the comparison of 12° vs. 30° screw angles, side-bending displacement was higher in the 30° group, but the difference was not statistically significant. However, in flexion, the 30° group showed a greater increase in displacement at higher torques, consistent with the expected biomechanical disadvantage at steeper trajectories **(Fig 1C&D)**.

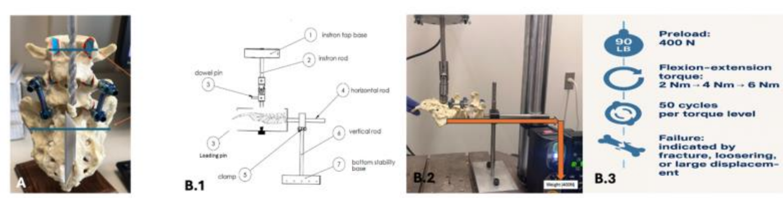
Construct stiffness analysis revealed a significant difference ($P < 0.05$) between the 12° and 30° spondylolysis groups, with mean slope values of 0.045 ± 0.022 and 0.021 ± 0.010, respectively, indicating greater stiffness in the 12° configuration. Following the observation of higher displacement in the 30° and spondylolisthesis constructs, interbody cages were added, and the tests were repeated. Results demonstrated a 50% reduction in displacement in the 12° group and 75% reduction in the 30° group, confirming the stabilizing effect of cage support, particularly in high-risk configurations.

DISCUSSION: Preliminary findings from this biomechanical study suggest that straighter pedicle screw trajectories and the use of interbody cages improve construct stability in L5-S1 fusion, particularly under flexion loading and in high-risk configurations, such as angled screws and spondylolisthesis models. While differences in displacement between groups were not always statistically significant, significant improvements in stiffness were observed in 12° constructs, and the addition of cages led to up to 75% reduction in displacement, reinforcing their stabilizing effect. These early results support the role of construct design in optimizing fusion outcomes in pediatric and young adult patients.

Limitations include the use of synthetic spine models, which may not fully replicate cadaveric bone properties, as well as simplified loading conditions that do not capture the effects of soft tissues, disc degeneration, or dynamic, multiplanar spinal forces. Ongoing destructive testing and complete groupwise comparisons will further validate the biomechanical relevance of these findings.

SIGNIFICANCE/CLINICAL RELEVANCE: Optimizing screw angle and incorporating interbody cages may reduce hardware failure risk in L5-S1 fusion, especially in patients with spondylolysis or low-grade spondylolisthesis. Straighter screw trajectories and cage support were associated with reduced micromotion and increased construct stiffness. These findings may help optimize surgical decision-making in pediatric and young adult patients, where minimizing hardware failure is critical.

FIGURES:



A: An instrumented model,
B: Test set-up and protocol,
C.1: Total Displacement for Spondylolisthesis vs Spondylolysis,
C.2: Total Displacement for 12-degree vs 30-degree,
D.1: Flexion Displacement in Sagittal axis (P= 0.753) for Spondylolisthesis vs Spondylolysis,
D.2: Flexion Displacement in Sagittal axis (P= 0.5) for 12-degree vs 30-degree