Biomechanical assessment of proximal junctional semi-rigid fixation in long-segment thoracolumbar constructs

Vibhu K. Viswanathan, MBBS,¹ Ranjit Ganguly, MD,¹ Amy J. Minnema, MS,¹
Nicole A. DeVries Watson, PhD,⁴ Nicole M. Grosland, PhD,^{2–4} Douglas C. Fredericks, BS,²
Andrew J. Grossbach, MD,¹ Stephanus V. Viljoen, MD,¹ and H. Francis Farhadi, MD, PhD¹

¹Department of Neurological Surgery, The Ohio State University Wexner Medical Center, Columbus, Ohio; and Departments of

²Orthopaedics and Rehabilitation and ³Biomedical Engineering, and ⁴Center for Computer Aided Design, University of Iowa, Iowa City, Iowa

OBJECTIVE Proximal junctional kyphosis (PJK) and failure (PJF) are potentially catastrophic complications that result from abrupt changes in stress across rigid instrumented and mobile non-fused segments of the spine (transition zone) after adult spinal deformity surgery. Recently, data have indicated that extension (widening) of the transitional zone via use of proximal junctional (PJ) semi-rigid fixation can mitigate this complication. To assess the biomechanical effectiveness of 3 semi-rigid fixation constructs (compared to pedicle screw fixation alone), the authors performed cadaveric studies that measured the extent of PJ motion and intradiscal pressure changes (Δ IDP).

METHODS To measure flexibility and Δ IDP at the PJ segments, moments in flexion, extension, lateral bending (LB), and torsion were conducted in 13 fresh-frozen human cadaveric specimens. Five testing cycles were conducted, including intact (INT), T10–L2 pedicle screw-rod fixation alone (PSF), supplemental hybrid T9 Mersilene tape insertion (MT), hybrid T9 sublaminar band insertion (SLB1), and hybrid T8/T9 sublaminar band insertion (SLB2).

RESULTS Compared to PSF, SLB1 significantly reduced flexibility at the level rostral to the upper-instrumented vertebral level (UIV+1) under moments in 3 directions (flexion, LB, and torsion, $p \leq 0.01$). SLB2 significantly reduced motion in all directions at UIV+1 (flexion, extension, LB, torsion, $p < 0.05$) and at UIV+2 (LB, torsion, $p \leq 0.03$). MT only reduced flexibility in extension at UIV+1 ($p = 0.02$). All 3 constructs revealed significant reductions in Δ IDP at UIV+1 in flexion (MT, SLB1, SLB2, $p \leq 0.02$) and torsion (MT, SLB1, SLB2, $p \leq 0.05$), while SLB1 and SLB2 significantly reduced Δ IDP in extension (SLB1, SLB2, $p \leq 0.02$) and SLB2 reduced Δ IDP in LB ($p = 0.05$). At UIV+2, SLB2 similarly significantly reduced Δ IDP in extension, LB, and torsion ($p \leq 0.05$).

CONCLUSIONS Compared to MT, the SLB1 and SLB2 constructs significantly reduced flexibility and Δ IDP in various directions through the application of robust anteroposterior force vectors at UIV+1 and UIV+2. These findings indicate that semi-rigid sublaminar banding can most effectively expand the transition zone and mitigate stresses at the PJ levels of long-segment thoracolumbar constructs.

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KEYWORDS proximal junctional kyphosis; proximal junctional failure; sublaminar band; Mersilene tape; spinal deformity; thoracic

PROXIMAL junctional kyphosis (PJK) and proximal junctional failure (PJF) are well-known complications following long-segment instrumented adult spinal deformity (ASD) surgery. PJK criteria include focal segmental kyphosis of 10° or more and a relative 10° or

more kyphotic increase between the upper instrumented vertebra (UIV) and 2 levels cranial to the UIV (UIV+2).⁷ With an incidence of 5.6%–21%,^{11,16} PJF is the most common cause for ASD revision surgery.²⁴ Despite the morbidity associated with PJK and PJF, the factors underlying

ABBREVIATIONS ASD = adult spinal deformity; BMD = bone mineral density; CT = computed tomography; INT = intact; LB = lateral bending; MT = Mersilene tape; PJ = proximal junctional; PJF = PJ failure; PJK = PJ kyphosis; PSF = pedicle screw fixation; SLB1 = sublaminar band at UIV+1; SLB2 = sublaminar band at UIV+1 and UIV+2; UIV = upper instrumented vertebra; Δ IDP = change in intradiscal pressure.

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their development have not been completely defined.^{4,5} However, data indicate that the abrupt change in stress between the rigid instrumented vertebral segments and the adjacent mobile vertebrae represents the most critical biomechanical factor in the development of PJK and PJF.³

To reduce the development of PJK and PJF after long-segment instrumented fusion, semi-rigid implants connecting the proximal portion of the instrumented fusion to the non-instrumented spine have been developed. These constructs are designed to widen the transition zone and reduce stress across this region.^{1,2,26,30} One proposed model involves the use of posterior tethers proximal to the UIV.² Specifically, augmentation of the posterior spinal ligamentous complex using either spinous process-anchored Mersilene tape (MT; Ethicon)³⁰ or polyester sublaminar bands²⁷ positioned at the PJ levels and fastened to the long-segment construct has been employed to generate semi-rigid fixation with distinct force vectors. These hybrid constructs are designed to provide a smoother transition and to reduce the stress across the proximal junction, thereby preventing proximal flexion failure.²⁰

While these semi-rigid constructs have been employed clinically to potentially reduce PJK and PJF, the comparative biomechanical advantages of each of these constructs have not been defined. To characterize the biomechanical properties of various designs (compared to rigid instrumented fixation), we performed a cadaveric study examining a combination of rigid and PJ semi-rigid fixation constructs and determined if these designs impart an advantage against the development of known risk factors for PJK and PJF.

Methods

Experimental Study

Thirteen fresh frozen human thoracolumbar spines (T7–L2) were used in this study (5 female, 8 male; mean age 56.2 years, range 41–66 years). Specimens were screened based on age (< 70 years), absence of gross coronal or sagittal deformities, absence of lower thoracic bridging osteophytes, and absence of severe disc height loss that would preclude pressure needle placement. Additionally, a lower limit of 0.8 g/cm³ bone mineral density (BMD) on quantitative computed tomography (CT) was set for inclusion (mean 1.04 g/cm³, range 0.81–1.17 g/cm³).

Quantitative CT Analysis

Dual-energy images (80 kV and 150 kV) were acquired using a CT scanner with an in-plane resolution of 0.3 × 0.3 mm and 3-mm axial sections. The 150-kV scans were analyzed using ITK-SNAP by segmenting axial slices at approximately mid-vertebral body height while ensuring exclusion of cortical bone. For each specimen, BMD was calculated in Hounsfield units at individual vertebral body levels. The BMD correlation was determined with the Gammex phantom scanned using the same parameters as above. The phantom provided known densities for several materials, including air, cortical bone, and cancellous bone.

Specimen Preparation

All specimens were stored at –20°C prior to biome-

chanical testing. The specimens were thawed to room temperature, and the paravertebral musculature was carefully removed, leaving all ligamentous structures intact. The most cephalad and caudal vertebrae of each specimen were mounted in polyester resin casts (Bondo Corp.). Wood screws were used to help anchor the vertebral bodies within the potting material. To prevent dehydration, the specimens were routinely irrigated with a 0.9% sodium chloride solution throughout the test period.

Motion Testing

A servo-hydraulic MTS 858 Bionix II configured with 2 spine gimbals (MTS Corp.) was used to apply unconstrained load application in all 6 degrees of freedom, namely in flexion, extension, lateral bending, and torsion. Intersegmental motion was assessed via specialized markers rigidly affixed to each vertebral level. Each marker consisted of 3 non-collinear infrared light-emitting diodes detectable by an optoelectronic motion analysis system (Optotrak 3020, Northern Digital Inc.).

Specimens were tested using a hybrid multidirectional test protocol.²⁰ Initially, intact specimens were loaded to a known moment and the resulting motions were recorded. Thereafter, following the desired intervention (e.g., pedicle ± hybrid fixation; see Fig. 1), the specimens were rotated to achieve the range of motion exhibited by the intact specimen. This protocol allows for determination of the effect of the surgical intervention on the instrumented and adjacent intervertebral levels.

For the first motion test, the intact thoracolumbar spine segments were tested nondestructively in a random sequence of flexion/extension (x-axis), bilateral torsion (axial rotation) (y-axis), and bilateral lateral bending (z-axis) via the moment loading system set to ± 4 Nxm.¹⁸ In subsequent flexibility tests, the specimens were loaded to obtain the same range of motion as that obtained in the intact condition. However, given the number of planned experimental cycles, the maximum moment was limited to ± 6 Nxm to prevent destructive loading of the specimens.²³ All tests were repeated for 3 successive loading and unloading cycles, with the data from the third cycle contributing to the computational analyses. Normalized motion values were calculated to control for interspecimen stiffness differences. Motion at the T11–L2 to L1–2 levels was averaged and reported as a single value (T11–L2).

Intradiscal pressures at the PJ motion segments T8–9 and T9–10 as well as at T10–11 (UIV motion segment) were measured using Mikro-Cath pressure transducers (Millar Instruments). Transducers were advanced in an anterior to posterior direction to a depth of 15 mm into adjacent intervertebral discs. At T9–10, dual transducers separated by 5 mm were positioned, and the average values were reported.

Testing Paradigm

All specimens underwent testing in 5 sequential cycles.

1. Intact (INT). Spines were tested intact to assess normal ranges of motion prior to fixation.
2. Pedicle screw fixation (PSF). Pedicle screws (5.5 ×

FIG. 1. Photographs of 3 hybrid constructs. **A:** MT construct. **B:** SLB1 construct showing placement of bilateral sublamina bands at the T9 level. **C:** SLB2 construct showing placement of bilateral sublamina bands at the T8 and T9 levels.

45 mm polyaxial screws; Medtronic) were inserted at the T10, T11, T12, L1, and L2 levels using a free-hand technique with subsequent probing of all the tracts to ensure circumferential walls. Titanium rods were then positioned spanning T10–L2 and firmly fixed within the potting to further ensure rigid caudal fixation.

3. Mersilene tape (MT). A hole was made at the base of the T9 spinous process using a penetrating towel clamp. MT was then passed through the base of the spinous process. The tape was tied to a transverse connector and distraction applied with a rod distractor prior to final tightening (Fig. 1A).
4. Single-level PJ sublamina band placement at T9 (SLB1). The MT was removed, and bilateral hemilaminotomies were fashioned at T9 and T10. Bilateral sublamina bands (Jazz; Implanet America Inc.) were placed at the T9 level. The bands were separately attached to the rods, and each band was tensioned using a torquemeter triggered at 2.5 Nxm bilaterally (Fig. 1B).
5. Double-level PJ sublamina band placement at T8 and T9 (SLB2). The previously positioned sublamina bands were removed, and bilateral hemilaminotomies were fashioned at T8. New bilateral bands were positioned at the T8 and T9 levels. Both bands at each level were separately attached to the rods, and each band was tensioned using a torquemeter triggered at 2.5 Nxm (Fig. 1C).

The posterior ligamentous structures and facet joints were kept intact during insertion of the MT and sublamina bands. The resultant force vectors produced by these hybrid construct designs are shown schematically in Fig. 2; MT insertion and final anchoring results in a rostrocau-

dal vector, while final tensioning of the sublamina bands (SLB1 and SLB2) produces a robust horizontal anterior-to-posterior vector.

Data Analysis

Load-displacement curves for each spinal level were derived and converted into range of motion¹⁹ and neutral zone²² for each of the flexibility tests. Intradiscal pressure changes (Δ IDP) were also compared for each loading paradigm.

Statistical Analysis

IBM SPSS Statistics v25 (IBM Corp.) was used for the data analysis. Considering the paired and non-parametric characteristics of the study data, Friedman's test (non-parametric ANOVA for repeated measures) was done to compare the overall effect of the configuration groups. In the case of a significant result, pairwise comparisons were performed to assess specific differences between hybrid fixation techniques (MT, SLB1, and SLB2) and PSF. Direct comparisons were made using the Wilcoxon signed-rank test with Bonferroni adjustment for 3 comparisons. Median values were compared after exclusion of major outliers. A p value ≤ 0.05 was considered statistically significant.

Results

Biomechanical Testing Characteristics

All the specimens ($n = 13$) underwent the first 4 cycles of testing (INT, PSF, MT, and SLB1), and 9 specimens underwent a further fifth cycle (SLB2). For each speci-

FIG. 2. Schematic diagram of PSF and the 3 hybrid constructs (MT, SLB1, and SLB2). The functional spinal units at the proximal junction exposed to high stress are shaded in gray. The MT, SLB1, and SLB2 vectors are depicted with arrows pointing in the direction of maximal applied force. Copyright The Ohio State University Wexner Medical Center. Published with permission.

men, PJ motion and intradiscal pressure analysis were performed under specific loads in different directions.

Motion Analysis

Segmental motion assessments were performed at the T7–8 to L1–2 levels for all 5 cycles (INT, PSF, MT, SLB1, and SLB2). The results for PSF, MT, SLB1, and SLB2 are

shown as percentages of segmental INT motion in Figs. 3–6 and Table 1. The range of motion at T9–10 (UIV+1) for each hybrid construct (MT, SLB1, and SLB2) was assessed separately for significant differences in comparison to the PSF construct. Significant motion restriction for SLB1 and SLB2 was noted at T9–10 in flexion (for SLB1 and SLB2, respectively: median 44.9%, IQR 34.7%–65.5%, $p = 0.01$;

FIG. 3. Only SLB1 and SLB2 show reduced motion at T9–10 as compared to PSF in flexion. **Left:** Box plots showing median (bold line inside box) percentage of intact flexion motion values at the T7–8, T8–9, T9–10, T10–11, and T11–L2 levels for PSF and the 3 hybrid constructs (MT, SLB1, and SLB2). The boxes indicate IQRs and the error bars indicate the minimum and maximum values. **Right:** Line graphs of flexion (in normalized degrees) showing a less abrupt transition (reduced slope) between the fixed and mobile transitional segments for the SLB1 and SLB2 constructs.

FIG. 4. Only MT and SLB2 show reduced motion at T9-10 as compared to PSF in extension. **Left:** Box plots showing median (bold line inside box) percentage of intact extension motion values at the T7-8, T8-9, T9-10, T10-11, and T11-L2 levels for PSF and the 3 hybrid constructs (MT, SLB1, and SLB2). The boxes indicate IQRs and the error bars indicate the minimum and maximum values. **Right:** Line graphs of extension (in normalized degrees) showing a less abrupt transition (reduced slope) between the fixed and mobile transitional segments for the MT and SLB2 constructs.

24.4%, IQR 21.6%–72.2%, $p = 0.02$), LB (median 76.4%, IQR 57.4%–80.6%, $p = 0.003$; 41.6%, IQR 34.1%–46.1%, $p = 0.02$) and torsion (median 43.3%, IQR 28.3%–48.3%, $p = 0.003$; 34.3%, IQR 26.0%–37.0%, $p = 0.02$). Further, SLB2 significantly restricted motion at UIV+1 in extension (median 21.5%, IQR 10.0%–36.9%, $p = 0.04$). In contrast, MT insertion resulted in a significant reduction in extension only at UIV+1 (median 46.9%, IQR 41.8%–59.4%, $p = 0.02$).

Range of motion restriction at T8-9 (UIV+2) and at T10-11 (UIV) for each hybrid construct was similarly assessed separately in comparison to the PSF construct (Figs. 3-6 and Table 1). At UIV+2, only SLB2 demonstrated significant motion restriction under moments of lateral bend-

ing (median 78.6%, IQR 71.2%–83.4%, $p = 0.03$) and torsion (median 48.6%, IQR 46.6%–65.5%, $p = 0.02$). Trends toward motion restriction for SLB2 were also noted in flexion (median 18.5%, IQR 3.4–48.8%, $p = 0.4$) and extension (median 33.1%, IQR 25.9%–50.0%, $p = 0.06$) but failed to achieve statistical significance. At UIV, SLB2 significantly restricted motion in LB (median 13.1%, IQR 6.4%–17.6%, $p = 0.02$). No restriction of motion at either T8-9 or T10-11 was noted with the MT and SLB1 hybrid constructs.

Intradiscal Pressure Analysis

Measurements of intradiscal pressure changes (Δ IDP) were performed at the T8-9, T9-10, and T10-11 intervertebral levels for each of the 5 cycles (INT, PSF, MT, SLB1,

FIG. 5. Only SLB1 and SLB2 show reduced motion at T9-10 as compared to PSF in lateral bending. SLB2 further reduces motion in LB at T8-9 and T10-11. **Left:** Box plots showing median (bold line inside box) percentage of intact lateral bending (LB) motion values at the T7-8, T8-9, T9-10, T10-11, and T11-L2 levels for PSF and the 2 hybrid constructs (MT, SLB1, and SLB2). The boxes indicate IQRs and the error bars indicate the minimum and maximum values. **Right:** Line graphs of LB (in normalized degrees) showing a less abrupt transition (reduced slope) between the fixed and mobile transitional segments for the SLB1 and in particular SLB2 constructs.

FIG. 6. Only SLB1 and SLB2 show reduced motion at T9-10 and SLB2 further shows reduced motion at T8-9 as compared to PSF in torsion. **Left:** Box plots showing median (bold line inside box) percentage of intact torsion motion values at the T7-8, T8-9, T9-10, T10-11, and T11-L2 levels for PSF and the 3 hybrid constructs (MT, SLB1, and SLB2). The boxes indicate IQRs and the error bars indicate the minimum and maximum values. **Right:** Line graphs of torsion (in normalized degrees) showing a less abrupt transition (reduced slope) between the fixed and mobile transitional segments for the SLB1 and in particular SLB2 constructs.

and SLB2; Fig. 7). Δ IDP at these intervertebral levels was compared to PSF for each hybrid construct. All 3 hybrid constructs significantly reduced Δ IDP at UIV+1 in flexion (MT -22.3%, IQR -111.9% to 18.8%, $p = 0.01$; SLB1 57.2%, IQR 20.8%–73.3%, $p = 0.01$; SLB2 26.8%, IQR -20.3% to 42.1%, $p = 0.02$) and torsion (MT 66.3%, IQR

37.8%–75.6%, $p = 0.03$; SLB1 25.9%, IQR 18.6%–40.5%, $p = 0.02$; SLB2 22.4%, IQR 12.4%–32.8%, $p = 0.05$). Moreover, while at UIV+1, SLB1 and SLB2 significantly reduced Δ IDP in extension (SLB1 38.4%, IQR 18.0%–57.4%, $p = 0.01$; SLB2 -0.9%, IQR -79.1% to 13.1%, $p = 0.02$), only SLB2 significantly reduced Δ IDP in LB (32.0%, IQR

TABLE 1. Motion analysis

	T8-9		T9-10		T10-11	
	% of INT	p Value	% of INT	p Value	% of INT	p Value
Flexion						
PSF	80.5 (52.3–92.0)	0.057	97.9 (73.6–132.3)	>0.99	8.0 (-0.8 to 26.2)	0.003
MT	69.7 (43.2–100.0)	>0.99	75.0 (48.2–111.8)	0.837	1.1 (-7.8 to 24.2)	>0.99
SLB1	84.5 (56.6–127.3)	>0.99	44.9 (34.7–65.5)	0.012	18.7 (-7.6 to 34.2)	>0.99
SLB2	18.5 (3.4–48.8)	0.417	24.4 (21.6–72.2)	0.024	6.1 (-5.4 to 32.0)	>0.99
Extension						
PSF	90.7 (75.8–125.7)	>0.99	96.6 (58.6–124.3)	>0.99	12.6 (5.6–27.8)	0.003
MT	95.6 (54.9–116.7)	>0.99	46.9 (41.8–59.4)	0.054	8.6 (2.7–30.6)	>0.99
SLB1	96.9 (66.4–126.8)	>0.99	35.7 (25.0–94.8)	0.180	15.6 (7.6–20.3)	>0.99
SLB2	33.1 (25.9–50.0)	0.063	21.5 (10.0–36.9)	0.040	6.4 (2.4–30.0)	>0.99
Lateral bending						
PSF	104.9 (98.1–110.2)	0.192	102.6 (97.5–107.2)	0.588	21.7 (20.8–31.2)	0.003
MT	109.6 (100.2–110.8)	>0.99	98.7 (68.3–103.9)	0.138	26.6 (22.6–32.4)	0.057
SLB1	105.2 (102.7–110.5)	0.627	76.4 (57.4–80.6)	0.003	20.2 (13.7–28.8)	0.099
SLB2	78.6 (71.2–83.4)	0.033	41.6 (34.1–46.1)	0.024	13.1 (6.4–17.6)	0.024
Torsion						
PSF	99.3 (90.7–103.5)	0.933	94.1 (91.0–97.8)	0.015	22.1 (17.1–27.2)	0.006
MT	98.2 (94.1–104.6)	>0.99	85.3 (77.7–100)	0.117	20.4 (10.6–30.5)	>0.99
SLB1	102.5 (95.2–105.9)	>0.99	43.3 (28.3–48.3)	0.003	16.7 (10.4–23.5)	0.297
SLB2	48.6 (46.6–65.5)	0.024	34.3 (26.0–37.0)	0.024	26.0 (23.3–28.2)	0.528

INT = intact; PSF = pedicle screw fixation; MT = Mersilene tape; SLB1 = sublaminar band at UIV+1; SLB2 = sublaminar band at UIV+1 and UIV+2. Data are presented as median (IQR). Boldface type indicates statistical significance.

FIG. 7. All 3 hybrid constructs show reduced Δ IDP in flexion and torsion at T9–10 as compared to PSF. SLB1 and SLB2 reduced Δ IDP at T9–10 in extension and SLB2 reduced Δ IDP in lateral bending (LB). SLB2 further reduced Δ IDP at T8–9 in extension, LB, and torsion. Box plots showing median (bold line inside box) percentage of intact flexion (A), extension (B), LB (C), and torsion (D) Δ IDP values at the T8–9, T9–10, and T10–11 levels for PSF and the 3 hybrid constructs (MT, SLB1, and SLB2). The boxes indicate IQRs and the error bars indicate the minimum and maximum values.

21.8%–37.1%, $p = 0.05$). Finally, at UIV+2, only SLB2 significantly reduced Δ IDP in extension (53.2%, IQR 45.6%–57.4%, $p = 0.05$), LB (68.4%, IQR 63.6%–84.9%, $p = 0.05$) and torsion (28.1%, IQR 17.5%–40.4%, $p = 0.04$).

Discussion

PJK and PJF Development

Enhanced quality of life and functional outcome measures following ASD surgery are directly related to the achievement of optimal thoracolumbar alignment.^{6,25} However, the restoration of ideal sagittal balance following long-segment thoracolumbar spinal fusion is associated with increased biomechanical stress at the PJ levels, which is directly implicated in the development of PJK and PJF.^{12,15,17}

Various global factors (including low BMD, older age, obesity, under- or overcorrection of pelvic or global sagittal alignment, the type/severity of underlying deformity, and underlying neuromuscular pathologies) and local junctional factors (including disruption of the posterior tension band, use of rigid instrumentation, improper end-

vertebra selection, and pre-existing proximal level disc degeneration) have been linked to the development of PJK and PJF.^{1,9,14,15,17,27–29} These factors likely further influence the abrupt changes in stress across the rigid instrumented and mobile non-fused segments of the spine.

Multiple hybrid constructs have been proposed to assist in transitional zone widening at the proximal end of long-segment constructs to reduce the strain placed on the adjacent motion segments.^{10,12,17,30} Recently, our clinical experience with sublaminar banding at the proximal end of long-segment thoracolumbar spinal fusion constructs to expand the transition zone has been associated with lower rates of PJK and prevention of PJF.²⁷ However, no comparative biomechanical studies have been undertaken to date to assess the potential advantage of such semi-rigid hybrid designs to mitigate PJ stress.

Preclinical PJK Studies

Finite element modeling studies have shown that significant abnormal biomechanical forces are present across the proximal end of long-segment fusion constructs. These pathologic forces result in increases in angular displace-

ment and intradiscal pressure that lead to PJK.^{2–4} Based on these studies, local biomechanical factors have been identified that can favorably influence these parameters. These factors include preservation of soft tissue elements, the presence of an anchor at the UIV, and the use of a transitional rod, as well as rod curvature and diameter. While supplemental transverse process hooks have not been shown to delay PJF in cadaveric biomechanical testing as compared to pedicle screw-only constructs,¹⁷ a more gradual transition has been demonstrated over the PJ levels when bilateral hooks replace bilateral UIV pedicle screws with an associated reduction in supra-adjacent segment hypermobility.^{18,26} Further, both PJ range of motion and intradiscal pressures were progressively reduced with increasing numbers of rostrally positioned posterior tethers in a recent long-segment finite element analysis.² Taken together, these studies confirm that rigid UIV fixation causes a significant stiffness differential at the PJ transition zone and that hybrid semi-rigid construct designs could counteract this biomechanical risk factor.

Current Study—Biomechanical Analysis

Biomechanical studies typically include assessments of load-displacement behavior of one or more functional spinal units (FSUs) under specific conditions.^{8,13,21} The standard universal protocols include range of motion, stiffness, and hybrid testing.^{13,21} The current study design mimics these protocols and prior PJK cadaveric studies in that specimens were unconstrained, with the magnitude and orientation of moments remaining the same with respect to the end vertebra.¹⁸ Previous studies have demonstrated reduced flexion stability, increased angular displacement, and an increase in intradiscal pressures at the levels proximal to the UIV secondary to instrumented fixation. Such biomechanical alterations have been shown to be further aggravated by the removal of supraspinous and interspinous ligaments.^{2,3}

MT restricted motion only under extension loads and reduced Δ IDP only under flexion and torsion moments at the UIV+1 level. As shown in Fig. 2, MT fastening results in a rostrocaudal force vector. If sufficiently taut, the PJ levels are brought into extension, thus leaving less available “reserve” for further movement, specifically in this direction. In contrast, sublaminar band placement resulted in more consistent PJ motion and Δ IDP reductions under loads applied in a majority of directions. Specifically, SLB1 reduced motion in all directions except in extension at UIV+1, and SLB2 was the only hybrid design to reduce motion in all directions at UIV+1 and to reduce motion at UIV+2, both in LB and torsion. Further, at the UIV, SLB2 restricted motion in LB, while no other construct offered any significant reduction in motion at this level. Δ IDP reductions were seen with SLB1 at UIV+1 (in all directions except LB) and with SLB2 at UIV+1 (in all directions) and UIV+2 (in all directions except for flexion). SLB2 appears to most optimally distribute stresses across the UIV+2 and UIV+1 PJ levels, thereby widening the transitional zone. The observed enhanced effects of banding at UIV+1 and UIV+2 are consistent with the finite element analysis of Bess and colleagues,² where multilevel posterior tethers progressively reduced PJ stresses.

The relative efficacy of sublaminar banding in mitigating PJ stresses relative to MT application appears likely due to the direction and magnitude of the applied force vectors (Fig. 2). While MT is anchored to a transverse connector at the UIV and offers a direct downward pull on the UIV+1 spinous process, sublaminar bands are tightly tensioned at the UIV+1 lamina in a direct anterior-to-posterior direction. This pull most effectively counteracts the post-instrumentation forward angular displacement force on the spine, which directly leads to PJK and PJF. Further, bilaterally positioned sublaminar bands provide greater stress shielding (as compared to a single MT) and render the proximal FSUs biomechanically more stable under physiological loads in various directions. Finally, laminae may represent more reliable anchors in osteoporotic spines, which are more prone to develop PJK and PJF.¹⁴

Conclusions

As compared to MT, sublaminar band placement yields maximal motion restriction and Δ IDP reduction at the proximal end of long-segment thoracolumbar constructs. Specifically, the use of sublaminar bands at 2 levels allows for the most gradual distribution of forces across the transitional segments.

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Author Contributions

Conception and design: Farhadi, Viswanathan, Minnema, DeVries Watson, Fredericks, Grosland, Viljoen. Acquisition of data: Farhadi, Viswanathan, Ganguly, DeVries Watson, Grossbach, Viljoen. Analysis and interpretation of data: Farhadi, Viswanathan, Ganguly, Minnema, DeVries Watson, Grosland, Viljoen. Drafting the article: Farhadi, Viswanathan, Ganguly, Minnema. Critically revising the article: Farhadi, Viswanathan, Minnema, DeVries Watson, Grosland, Grossbach, Viljoen. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Farhadi. Statistical analysis: Farhadi, Minnema. Administrative/technical/material support: Farhadi, Minnema, DeVries Watson, Grosland, Fredericks, Grossbach, Viljoen. Study supervision: Farhadi, Minnema, DeVries Watson, Fredericks, Viljoen.

Correspondence

H. Francis Farhadi: The Ohio State University Wexner Medical Center, Columbus, OH. francis.farhadi@osumc.edu.