Spine

SPINE Volume 48, Number 7, pp E94–E100

BIOMECHANICS

Hooks Versus Pedicle Screws at the Upper Instrumented Level

An In Vitro Biomechanical Comparison

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Study Design. Controlled laboratory study.

Objective. The aim was to compare motions at the upper instrumented vertebra (UIV) and supra-adjacent level (UIV+1) between two fixation techniques in thoracic posterior spinal fusion constructs. We hypothesized there would be greater motion at UIV +1 after cyclic loading across all constructs and bilateral pedicle screws (BPSs) with posterior ligamentous compromise would demonstrate the greatest UIV+1 range of motion.

Summary of Background Data. Proximal junctional kyphosis is a well-recognized complication following long thoracolumbar posterior spinal fusion, however, its mechanism is poorly understood.

Materials and Methods. Twenty-seven thoracic functional spine units were randomly divided into three UIV fixation groups ($n=9$): (1) BPS, (2) bilateral transverse process hooks (TPHs), and (3) BPS with compromise of the posterior elements between UIV and UIV+1 (BPS-C). Specimens were tested on a servohydraulic materials testing system in native state, following instrumentation, and after cyclic loading. functional spine units were loaded in flexion-extension (FE), lateral bending, and axial rotation.

Results. After cyclic testing, the TPH group had a mean 29.4% increase in FE range of motion at UIV+1 versus 76.6% in the BPS group ($P<0.05$). The BPS-C group showed an increased FE of 49.9% and 62.19% with sectioning of the facet joints and interspinous ligament respectively prior to cyclic testing.

Conclusion. BPSs at the UIV led to greater motion at UIV+1 compared to bilateral TPH after cyclic loading. This is likely due to the increased rigidity of BPS compared to TPH leading to a "softer" transition between the TPH construct and native anatomy at the supra-adjacent level. Facet capsule compromise led to a 49.9% increase in UIV+1 motion, underscoring the importance of preserving the posterior ligamentous complex. Clinical studies that account for fusion rates are warranted to determine if constructs with a "soft transition" result in less proximal junctional kyphosis *in vivo*.

Key words: proximal junctional kyphosis, biomechanical, posterior spinal fusion, thoracolumbar, PJK, pedicle screws, transverse process hooks

Spine 2023;48:E94–E100

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Acknowledgment date: August 17, 2022. First revision date: October 20, 2022. Acceptance date: November 12, 2022.

This research was supported in part by an appointment to the Department of Defense (DoD) Research Participation Program administered by the Oak Ridge Institute for Science and Education (ORISE) through an interagency agreement between the US Department of Energy (DoE) and the DoD. ORISE is managed by ORAU under DoE contract number DE-SC0014664. In addition, funding was provided for portions of this project through the Walter Reed National Military Medical Center Department of Research Programs Graduate Medical Education Research funds (PI: W.B.R.). The identification of specific products or scientific instrumentation is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the author(s), DoD, or any component agency. The views expressed in this paper are those of the authors and do not reflect the official policy of the DoE, ORAU/ORISE Department of the Army/Navy/Air Force, Uniformed Services University of the Health Sciences, DoD, or US Government.

This study was conducted following approval by the Walter Reed National Military Medical Center Institutional Review Board under protocol number WRNMMC-EDO-2020-0453 "Biomechanical Comparison of Fixation Techniques in the Upper Extremity"

The authors report no conflicts of interest.

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DOI: 10.1097/BRS.0000000000004547

Proximal junctional kyphosis (PJK) is a debilitating complication of posterior spinal fusion (PSF; Table 1). First described by Glattes *et al* in 2005,[1] PJK involves the development of a kyphotic deformity at the junction between a rigid fusion construct and the mobile motion segments immediately cephalad to the construct. Glattes defined PJK as an angle $\geq 10°$ in the sagittal plane

TABLE 1. List of Abbreviations

Abbreviation	Definition
PJK	Proximal junctional kyphosis
PSF	Posterior spinal fusion
UIV	Upper instrumented level
UIV+1	Vertebral level immediately cephalad to fusion
AIS	Adolescent idiopathic scoliosis
TPH	Transverse process hooks
BPS	Bilateral pedicle screws
ROM	Range of motion
PLC	Posterior ligamentous complex
BMD	Bone mineral density
FE	Flexion-extension
LB	Lateral bending
AR	Axial rotation
ISL	Interspinous ligament
BPS-C	Bilateral pedicle screws with compromised posterior ligaments

between the inferior endplate of the upper instrumented vertebra (UIV) and the superior endplate of the vertebra two levels supra-adjacent that is also $\geq 10°$ than the preoperative measurement.[1] Historically, PJK was thought to be a radiographic finding with little clinical significance, however, more recent literature has demonstrated PJK can lead to greater pain and worse clinical outcomes.[1–7] In severe cases, PJK may progress to proximal junctional failure requiring revision surgery.[8] Although PJK is a relatively common complication, affecting roughly 14% of adolescents and 30% of adults,[9,10] there is no consensus on the etiology or best prevention strategy. Multiple patient-related and surgical factors contribute to PJK, including construct rigidity, posterior ligamentous integrity, UIV selection, sagittal imbalance, and patient age.[1,2,9,11–22]

Advances in instrumentation have contributed to increased use of pedicle screws due to greater stability and deformity correction.[13,16,17,21] Unfortunately, the increased construct rigidity achieved with pedicle screws at the UIV may lead to increased rates of PJK.[2,5,9,16,21,22] Helgeson *et al*[21] performed a review of 283 adolescent idiopathic scoliosis (AIS) patients who were treated with PSF using pedicle screw, hook, or hybrid constructs and found a greater proximal junctional angle with pedicle screw constructs compared to those that used hooks at the UIV. Similarly, Kim *et al*[16] found greater PJK incidence in AIS patients treated with all-pedicle screw constructs compared to hook constructs. Additionally, they saw a similar increase when comparing hybrid to all hook constructs.[16] A similar study in adult patients found a greater rate of PJK in adult patients with PSF constructs that used pedicle screws at the UIV compared to hooks.[22]

Although clinical studies have demonstrated a link between construct rigidity and PJK, few studies have examined this biomechanical relationship *in vitro*. In a porcine model, Thawrani *et al*[20] demonstrated that bilateral transverse process hooks (TPHs) at the UIV led to lower stiffness at the UIV and less motion at UIV+1 compared to bilateral pedicle screw (BPS) constructs. Similarly, Facchinello *et al*[23] found that PSF constructs using less stiff rods and TPH at the UIV allowed for a more gradual transition in stiffness between the UIV and UIV+1. Metzger *et al*[24] performed an *in vitro* study in human thoracic spine specimens to compare PSF construct rigidity utilizing BPS, supralaminar hooks, or a unilateral hook and pedicle screw at the UIV. They found greater range of motion (ROM) at UIV+1 in BPS constructs compared to the hook and hybrid constructs.[24] Several biomechanical studies have also demonstrated the contribution of posterior ligamentous complex (PLC) structures to PSF proximal junction stability.[24–26]

While these biomechanical studies highlight the relationship between PSF construct rigidity and proximal junction mobility at time-zero, they are limited in that these tests were quasistatic. PJK develops and progresses over time and is most commonly diagnosed within the first postoperative year but can be evident within three months postsurgery.[2,4] The spine experiences roughly 2200 motion cycles per day,[27] and quasistatic ROM tests may not represent the true effect of PSF constructs on junctional motion. Cyclic biomechanical testing allows approximation of *in vivo* postoperative motion by subjecting specimens to thousands of motion cycles. There is a dearth of literature utilizing cyclic motion protocols to evaluate PSF construct rigidity and PJK risk.

The purpose of this study was to compare proximal junction ROM between PSF constructs using either BPS or TPH at the UIV before and after cyclic loading. The secondary purpose was to evaluate ROM at the proximal junction following PLC compromise under cyclic load. We hypothesized that there would be greater ROM at UIV+1 in the pedicle screw group compared to the TPH group, and PLC compromise would lead to the greatest ROM increase.

MATERIALS AND METHODS

Specimens

Nine cadaveric thoracolumbar spines (T3-L2) were procured and stored at –30°C. The specimens were screened for deformities, bone mineral density, and prior injuries and instrumentation. Specimens were cleaned of nonstructural soft tissue, preserving the ligaments, joint articulations, transverse processes, and intervertebral disks. Each specimen was disarticulated into 3 functional spine units (FSUs): T3-T6, T7-T10, and T11-L2. The cranial and caudal vertebrae were potted at approximately half-axial height in polyvinyl chloride cups using 1:1 Bondo and fiberglass resin mixture (Bondo; 3M Company, St. Paul, MN) for rigid fixation to the testing system.

Biomechanical Testing

FSUs were mounted on a servohydraulic material testing system augmented with a Spine Test Fixture (MTS 858 Mini

Figure 1. Anterior aspect of a vertebral motion segment mounted in the servohydralic testing system with optical tracking sensors affixed.

Bionix II; MTS Systems Corp., Eden Prairie, MN; Fig. 1). The caudal pot was affixed to a lower base mounted on X-Y linear railing for passive translation. The cephalad pot was affixed to an upper base mounted to the Spine Test Fixture for applying bending rotations and torques. An infrared rigid body marker (Optotrak Certus; Northern Digital Inc., Waterloo, Ontario, CA) was attached to the anterior aspect of each vertebral body to record three-dimensional vertebral kinematics (Fig. 1). FSUs were nondestructively bent in flexion-extension (FE), lateral bending (LB), and axial rotation (AR) under angular control at a 0.5°/s rate with a constant 10 N axial compression preload throughout and until the predetermined 5 Nm torque limit was reached. Bending in each direction was repeated three times to minimize creep; ROM was recorded during the third repetition.

Experimental Design

Once the intact ROMs were evaluated, matched FSUs from the same cadaver were randomly assigned to one of three groups. Each group was instrumented with pedicle screws at the lower exposed level and UIV instrumentation according to group assignment. One group was instrumented with BPS at the UIV, one with TPH at the UIV, and one with BPS that underwent sequential sectioning of the bilateral facet joints and interspinous ligament (ISL) between the UIV and UIV+1 prior to cyclic testing (BPS-C). Each FSU was then potted with the distal aspect of the rods incorporated into the potting to simulate a long construct.[26] Following instrumentation, ROMs were evaluated again using the same testing procedure described above. The instrumented FSU were fatigued with cyclic loading in FE (±5 Nm) at 1 Hz rate for 20,000 cycles. ROMs were evaluated again after cyclic loading. As there is little literature regarding cyclic testing in the spine, 20,000 cycles was chosen to maximize motion cycles while preserving cadaveric specimens for the duration of the experiment.

Surgical Treatment

Specimens were instrumented by one of two fellowship-trained spine surgeons. Once the soft tissues were removed, pedicle screw start points were prepared with a 3 mm high-speed burr (Medtronic, Fridley, MN) and an awl. Screw depth was measured using a blunt-tip probe and ruler and 5.5 mm polyaxial pedicle screws (Medtronic) were placed. Screw placement was confirmed via fluoroscopy and then 3.5 mm titanium rods were contoured and secured with set screws. In the TPH group, appropriately sized TPH (Depuy, Westchester, PA) were anchored to the transverse process at the UIV and secured to the rods with set screws. Rods were then incorporated into potting as described above.

Data Reduction

Three-dimensional vertebral motions were processed, filtered using a fourth-order zero-lag Butterworth filter (f_s = 100 Hz, f_c = 1 Hz), and converted into Euler angles with custom MATLAB scripts (vR2020a; MathWorks Inc., Natick, MA). Euler angles were translated to vertebral ROMs in FE, LB, and AR. The segmental ROM at UIV/UIV+1 were calculated and normalized to their respective intact ROMs as percentage change relative to intact.

Statistical Analysis

Percentage change in FE, LB, and AR ROMs from intact before and after cyclic loading were compared between the three groups using two-way mixed analysis of variance followed by Bonferroni-adjusted *post hoc* pairwise comparisons ($P < 0.05$). The number of cycles to failure for specimens that failed prior to 20,000 cycles was compared between the three groups using Kruskal-Wallis test. All statistical analyses were performed using R (v4.0.2; Vienna, Austria) in RStudio (v1.3; RStudio, Inc., Boston, MA).

RESULTS

Prefatigue Testing

There was no significant difference in percentage change in ROM from intact at UIV+1 after instrumentation between TPH and BPS (Fig. 2, Table 2). FE ROM at UIV+1 increased by 49.9% after facet joint violation (Fig. 2) in the BPS-C group. FE ROM at UIV+1 did not change after ISL violation compared to facet joint violation alone prior to

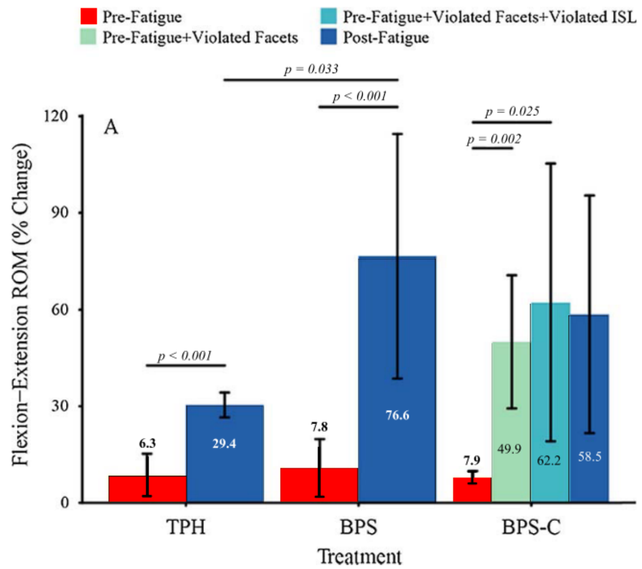

Figure 2. Percent change in flexion-extension range of motion (ROM) at upper instrumented vertebra (UIV)+1 from uninstrumented motion segments following 20,000 flexion-extension cycles at 5° per second under 10 N axial compression. BPS indicates bilateral pedicle screws at the UIV; BPS-C, bilateral pedicle screws at the UIV with sequential compromise of the facet joints and interspinous ligament; TPH, bilateral transverse process hooks at the UIV.

cyclic loading ($P = 0.493$; Fig. 2). Facet joint violations and the subsequent ISL violation had no effect on LB and AR ROM at UIV+1 compared to each other and the ROMs measured at initial prefatigue instrumentation (Figs. 3, 4, Table 2).

Postfatigue Testing

After cyclic loading, the BPS group demonstrated more FE ROM at UIV+1 compared to the TPH group (Fig. 2). No difference was found in FE ROM at UIV+1 between TPHs and BPS-C or between BPS without and with PLC compromise. The percentage change in ROM from native at UIV+1 after initial instrumentation did not differ for LB and AR ROM across all groups (Figs. 3, 4). There was no difference in ROM between specimens with respect to UIV level ($P > 0.05$ for all planes).

FE ROM at UIV+1 increased from prefatigue to postfatigue in both the TPH and BPS group (Fig. 2). Within the BPS-C group, there were no differences in FE ROM after ISL violation and cyclic loading relative to the ROM evaluated after the facet joints alone were violated (Fig. 2).

LB ROM at UIV+1 increased after cyclic loading compared to prefatigue instrumentation within the BPS group (Fig. 3). There were no differences in LB ROM at UIV+1 between prefatigue and postfatigue instrumentation within the TPHs and BPS with sequential sectioning groups (Fig. 3). AR ROM at UIV+1 increased after cyclic loading compared to prefatigue instrumentation in the TPH group (Fig. 4). No differences were found in AR ROM at UIV+1 between prefatigue and postfatigue instrumentation in the BPS groups without and with sequential posterior element compromise (Fig. 4).

TABLE 2. Percent Increase in Range of Motion at UIV+1 as Compared to Uninstrumented Specimens in Flexion-Extension, Lateral Bending, and Axial Rotation

	Flexion-extension			Lateral bending			Axial rotation		
	TPH	BPS	BPS-C	TPH	BPS	BPS-C	TPH	BPS	BPS-C
Prefatigue	6.3 ± 2.2	7.8 ± 4.5	7.9 ± 1.9	24.5 ± 19.4	28.3 ± 13.8	20.5 ± 17.0	15.5 ± 12.5	66.4 ± 37.6	57.8 ± 26.5
Facet joints violation	—	—	49.9 ± 20.6	—	—	31.1 ± 20.1	—	—	56.9 ± 39.3
ISL violation	—	—	62.2 ± 43.1	—	—	41.1 ± 27.5	—	—	61.2 ± 43.8
Postfatigue	29.4 ± 3.7	76.6 ± 32.9	58.5 ± 36.9	55.3 ± 36.0	68.8 ± 32.8	54.8 ± 23.7	44.7 ± 19.3	75.6 ± 32.8	76.2 ± 47.5

Prefatigue measurements taken following instrumentation. Postfatigue measurements represent motion following 20,000 flexion-extension cycles at 5° per second under 10 N axial compression. BPS indicates bilateral pedicle screws at the UIV; BPS-C, bilateral pedicle screws at the UIV with sequential compromise of the facet joints and interspinous ligament; ISL, interspinous ligament; TPH, bilateral transverse process hooks at the UIV; UIV, upper instrumented vertebra.

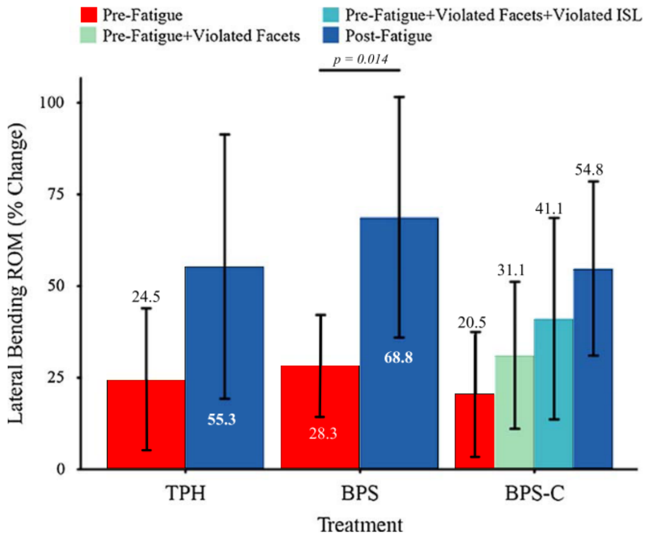

Figure 3. Percent change in lateral bending range of motion (ROM) at upper instrumented vertebra (UIV)+1 from uninstrumented motion segments following 20,000 flexion-extension cycles at 5° per second under 10 N axial compression. BPS indicates bilateral pedicle screws at the UIV; BPS-C, bilateral pedicle screws at the UIV with sequential compromise of the facet joints and interspinous ligament; TPH, bilateral transverse process hooks at the UIV.

Cyclic Failure

For specimens that failed prior to 20,000 cycles (TPH: n = 4, BPS: n = 3, BPS-C: n = 3), there was no difference in the number of cycles survived (2995 ± 5024 vs. 3347 ± 2209 vs. 1068 ± 764; $P = 0.453$).

Specimen Characteristics

There were no between-group differences in bone mineral density at the UIV or total specimen mean ($P = 0.860$ and

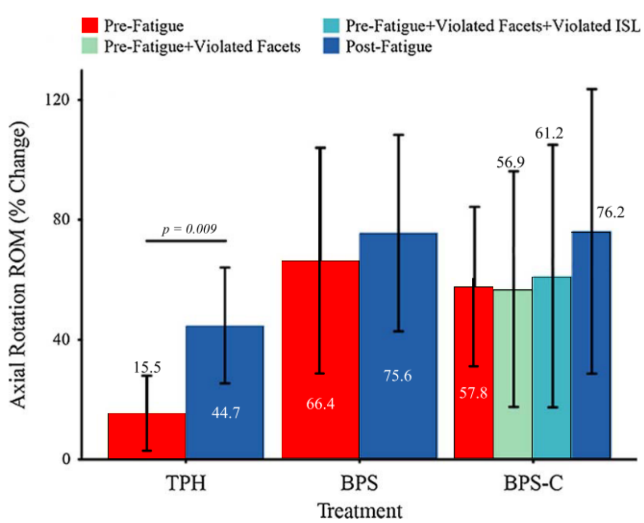

Figure 4. Percent change in axial rotation range of motion (ROM) at upper instrumented vertebra (UIV)+1 from uninstrumented motion segments following 20,000 flexion-extension cycles at 5° per second under 10 N axial compression. BPS indicates bilateral pedicle screws at the UIV; BPS-C, bilateral pedicle screws at the UIV with sequential compromise of the facet joints and interspinous ligament; TPH, bilateral transverse process hooks at the UIV.

0.840, respectively). In addition, there was no difference in ROM in any direction based on the UIV level in prefatigue or postfatigue testing.

DISCUSSION

The etiology of PJK is multifactorial, and the PLC is a critical component in maintaining sagittal alignment following PSF.[16,20–24] The purpose of this study was to determine if TPH or BPS creates a "soft transition" in the setting of a long posterior thoracic fusion. This soft transition may protect the PLC structures thereby mitigating the risk of PJK. We found a statistically significant increase in FE ROM at UIV+1 in the BPS group compared to the TPH group after cyclic loading. These results demonstrate how TPH provides a "soft transition" compared to BPS. The secondary aim was to evaluate the importance of PLC integrity to proximal junction mobility. Facet joint violation led to a nearly 50% increase in ROM at UIV+1, and this motion did not significantly increase when the ISL was sectioned as well. These findings further emphasize the importance of the PLC in the setting of PSF.

Cyclic loading was performed in this study to better replicate the functional loads the spine experiences postoperatively. In a similar study, Metzger *et al*[24] investigated the effect of differing UIV instrumentation in PSF constructs on ROM at the UIV and UIV+1. They found that ROM at UIV+1 increased in flexion with increasing construct stiffness, and BPS led to the most flexion compared to a hybrid or a bilateral lamina hook construct. They also found greater ROM in LB and AR with BPS compared to other constructs.[24] Our study measured change in ROM at UIV+1 between specimens prior to and after instrumentation, whereas Metzger and colleagues measured change in ROM as a percentage of the entire specimen ROM. In a porcine model, Thawrani *et al*[20] found increased ROM at UIV+1 in BPS constructs compared to TPH. While Thawrani *et al*[20] utilized full porcine spine specimens, Metzger *et al*[24] used short segment thoracic spines more similar to the FSU in this study and found that short spine segments can be adequately used to analyze motion and stiffness in PSF constructs. Additionally, Cammarata *et al*[18] performed a finite element analysis of PSF constructs and risk factors for PJK and found that TPH at the UIV led to decreased rigidity at the proximal junction and less risk for PJK compared to BPS constructs. The results of these studies support our major findings in the postfatigue data that TPH at the UIV led to a smoother transition zone between the PSF construct and native compared to BPS constructs.

This study also demonstrates the importance of maintaining PLC structures during thoracic PSF. Facet capsule compromise led to 49.9% increased FE ROM at UIV+1. These results are similar to findings by Anderson *et al*,[25] who performed a biomechanical analysis of UIV+1 motion after a series of posterior spine procedures. They sequentially performed potentially destabilizing procedures and found 6.59% loss of flexion stiffness after ISL sectioning followed by an additional 44.72% loss of flexion stiffness after facet capsule sectioning.[25] Although we sectioned the facet capsule first in this study, the results are similar in that UIV+1 motion increased most after this step, and marginally after ISL sectioning. Kim *et al*[15] had similar findings in that sectioning the ISL did not lead to a significant change in ROM at UIV+1 in a BPS PSF construct. In a finite element model, Aubin *et al*[28] found an increased flexion angle at UIV+1 by 10%, 28%, and 53% when the bilateral facet joints, ISL, and a combination of both structures. These studies and our findings highlight the importance of maintaining the facet capsule during PSF instrumentation. Additionally, facet capsule integrity may serve as another risk factor for PJK when using BPS at the UIV, as pedicle screw insertion poses a higher risk of facet joint violation than TPH insertion.[24]

This study has several limitations. This study does not address the tradeoff between PJK and pseudoarthrosis. There is sparse literature examining the tradeoff of increased rigidity and fusion rates in long PSFs. Theoretically, a less rigid construct may decrease the rate of PJK while increasing the rate of pseudoarthrosis. While there is a paucity of literature regarding adult deformity correction, two studies examining AIS found no significant difference in pseudoarthrosis rates between hook and pedicle screw constructs.[29,30] This is an important clinical question which warrants further investigation. Additionally, our findings remain limited by the limitations of a cadaveric study. Although the three groups in the study were adequately powered, these constructs were implemented at different vertebral levels in a simulated long construct. Previous studies have demonstrated UIV location in the thoracolumbar spine may predispose patients to PJK.[1,31–33] Unfortunately, the subgroups of differing constructs with similar UIV are underpowered to detect a meaningful difference, but there was no significant difference in UIV+1 motion when comparing UIV level across all constructs. Conversely, the consistent increase in UIV+1 motion in the BPS group across all UIV levels may strengthen the conclusion that TPH at the UIV in long PSF constructs may lead to decreased risk of PJK regardless on UIV level. Finally, this study did not evaluate motion changes at UIV+2, which can be used to evaluate PJK as described by Glattes *et al*.[1] Despite this limitation, this study was able to determine significant differences in motion at UIV+1 between UIV anchor types under cyclic load.

CONCLUSION

BPSs at the UIV led to greater motion at UIV+1 compared to bilateral TPH after cyclic loading. This is likely due to the increased rigidity of BPS compared to TPH leading to a "softer" transition between the TPH construct and native anatomy at the supra-adjacent level. Facet capsule compromise led to a 49.9% increase in UIV+1 motion, underscoring the importance of preserving the PLC. Clinical studies that account for fusion rates are warranted to determine if constructs with a "soft transition" result in less PJK *in vivo*.

➢ Key Points

- ❑ Using BPSs at the upper instrumented level of PSF constructs led to greater motion at the superior-adjacent level as compared to TPHs after cyclic loading.
- ❑ Violation of the facet joint capsule led to an almost 50% increase in motion at the superior-adjacent level. Maintenance of the posterior ligamentous structures is key to minimizing risk of PJK.
- ❑ Clinical in vivo studies that account for fusion rates are warranted to determine if less rigid instrumentation at the upper level of PSF constructs leads to less PJK.

References

1. Glattes RC, Bridwell KH, Lenke LG, Kim YJ, Rinella A, Charles Edwards I. Proximal junctional kyphosis in adult spinal deformity following long instrumented posterior spinal fusion: incidence, outcomes, and risk factor analysis. *Spine*. 2005;30: 1643–9.
2. Kim HJ, Iyer S. Proximal junctional kyphosis. *J Am Acad Orthop Surg*. 2016;24:318–26.
3. Yagi M, Akilah KB, Boachie-Adjei O. Incidence, risk factors and classification of proximal junctional kyphosis: surgical outcomes review of adult idiopathic scoliosis. *Spine*. 2011;36:E60–8.
4. Kim YJ, Bridwell KH, Lenke LG, Glattes CR, Rhim S, Cheh G. Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion—minimum five-year follow-up. *Spine*. 2008;33:2179–84.
5. Kim YJ, Bridwell KH, Lenke LG, Kim J, Cho SK. Proximal junctional kyphosis in adolescent idiopathic scoliosis following segmental posterior spinal instrumentation and fusion: minimum 5-year follow-up. *Spine*. 2005;30:2045–50.
6. Kim HJ, Bridwell KH, Lenke LG, et al. Proximal junctional kyphosis results in inferior SRS pain subscores in adult deformity patients. *Spine*. 2013;38:896–901.
7. Kim HJ, Bridwell KH, Lenke LG, et al. Patients with proximal junctional kyphosis requiring revision surgery have higher post-operative lumbar lordosis and larger sagittal balance corrections. *Spine*. 2014;39:E576–80.
8. Yagi M, Rahm M, Gaines R, et al. Characterization and surgical outcomes of proximal junctional failure in surgically treated patients with adult spinal deformity. *Spine*. 2014;39:E607–14.
9. Zhong JL, Cao K, Wang B, et al. Incidence and risk factors for proximal junctional kyphosis in adolescent idiopathic scoliosis after correction surgery: a meta-analysis. *World Neurosurg*. 2019;125:E326–35.
10. Liu FY, Wang T, Yang SD, Wang H, Yang DL, Ding WY. Incidence and risk factors for proximal junctional kyphosis: a meta-analysis. *Eur Spine J*. 2016;25:2376–83.
11. Cho KJ, Suk SI, Park SR, et al. Risk factors of sagittal decompensation after long posterior instrumentation and fusion for degenerative lumbar scoliosis. *Spine*. 2010;35:1595–601.
12. Han S, Hyun SJ, Kim KJ, Jahng TA, Lee S, Rhim SC. Rod stiffness as a risk factor of proximal junctional kyphosis after adult spinal deformity surgery: comparative study between cobalt chrome multiple-rod constructs and titanium alloy two-rod constructs. *Spine J*. 2017;17:962–8.
13. Hwang SW, Samdani AF, Wormser B, et al. Comparison of 5-year outcomes between pedicle screw and hybrid constructs in adolescent idiopathic scoliosis—clinical article. *J Neurosurg Spine*. 2012;17:212–9.

14. Kim HJ, Lenke LG, Shaffrey CI, Van Alstyne EM, Skelly AC. Proximal junctional kyphosis as a distinct form of adjacent segment pathology after spinal deformity surgery a systematic review. *Spine*. 2012;37:S144–64.
15. Kim JS, Cheung ZB, Arvind V, Caridi J, Cho SK-W. Role of posterior ligamentous reinforcement in proximal junctional kyphosis: a cadaveric biomechanical study. *Asian Spine J*. 2019;13:68–76.
16. Kim YJ, Lenke LG, Bridwell KH, et al. Proximal junctional kyphosis in adolescent idiopathic scoliosis after 3 different types of posterior segmental spinal instrumentation and fusions: incidence and risk factor analysis of 410 cases. *Spine*. 2007;32:2731–8.
17. Lau D, Clark AJ, Scheer JK, et al. Proximal junctional kyphosis and failure after spinal deformity surgery: a systematic review of the literature as a background to classification development. *Spine*. 2014;39:2093–102.
18. Cammarata M, Aubin CE, Wang XY, Mac-Thiong JM. Biomechanical risk factors for proximal junctional kyphosis a detailed numerical analysis of surgical instrumentation variables. *Spine*. 2014;39:E500–7.
19. Cammarata M, Wang X, Mac-Thiong J, Ce A. Biomechanical analysis of proximal junctional kyphosis: preliminary results. *Stud Health Technol Inform*. 2012;176:299–302.
20. Thawrani DP, Glos DL, Coombs MT, Bylski-Austrow DI, Sturm PF. Transverse process hooks at upper instrumented vertebra provide more gradual motion transition than pedicle screws. *Spine*. 2014;39:E826–32.
21. Helgeson MD, Shah SA, Newton PO, et al. Evaluation of proximal junctional kyphosis in adolescent idiopathic scoliosis following pedicle screw, hook, or hybrid instrumentation. *Spine*. 2010;35:177–81.
22. Hassanzadeh H, Gupta S, Jain A, El Dafrawy MH, Skolasky RL, Kebaish KM. Type of anchor at the proximal fusion level has a significant effect on the incidence of proximal junctional kyphosis and outcome in adults after long posterior spinal fusion. *Spine Deform*. 2013;1:299–305.
23. Facchinello Y, Brailovski V, Petit Y, Brummund M, Tremblay J, Mac-Thiong JM. Biomechanical assessment of the stabilization capacity of monolithic spinal rods with different flexural stiffness and anchoring arrangement. *Clin Biomech*. 2015;30:1026–35.
24. Metzger MF, Robinson ST, Svet MT, Liu JC, Acosta FL. Biomechanical analysis of the proximal adjacent segment after multilevel instrumentation of the thoracic spine: do hooks ease the transition? *Glob Spine J*. 2016;6:335–43.
25. Anderson AL, McIff TE, Asher MA, Burton DC, Glattes RC. The effect of posterior thoracic spine anatomical structures on motion segment flexion stiffness. *Spine*. 2009;34:441–6.
26. Mar DE, Burton DC, McIff TE. Biomechanics of prophylactic tethering for proximal junctional kyphosis: comparison of posterior tether looping techniques. *Spine Deform*. 2019;7:197–202.
27. Rohlmann A, Consmüller T, Dreischarf M, et al. Measurement of the number of lumbar spinal movements in the sagittal plane in a 24-hour period. *Eur Spine J*. 2014;23:2375–84.
28. Aubin C-E, Cammarata M, Wang X, Mac-Thiong J-M. Instrumentation strategies to reduce the risks of proximal junctional kyphosis in adult scoliosis: a detailed biomechanical analysis. *Spine Deform*. 2015;3:211–8.
29. Wu X, Yang S, Xu W, et al. Comparative intermediate and long-term results of pedicle screw and hook instrumentation in posterior correction and fusion of idiopathic thoracic scoliosis. *J Spinal Disord Tech*. 2010;23:467–73.
30. Kuklo TR, Potter BK, Lenke LG, Polly DW Jr, Sides B, Bridwell KH. Surgical revision rates of hooks versus hybrid versus screws versus combined anteroposterior spinal fusion for adolescent idiopathic scoliosis. *Spine*. 2007;32:2258–64.
31. Bridwell KH, Lenke LG, Cho SK, et al. Proximal junctional kyphosis in primary adult deformity surgery: evaluation of 20 degrees as a critical angle. *Neurosurgery*. 2013;72:899–906.
32. Ha Y, Maruo K, Racine L, et al. Proximal junctional kyphosis and clinical outcomes in adult spinal deformity surgery with fusion from the thoracic spine to the sacrum: a comparison of proximal and distal upper instrumented vertebrae. *J Neurosurg Spine*. 2013;19:360–9.
33. Maruo K, Ha Y, Inoue S, et al. Predictive factors for proximal junctional kyphosis in long fusions to the sacrum in adult spinal deformity. *Spine*. 2013;38:E1469–76.