Biomechanical Analysis of Multilevel Posterior Cervical Spinal Fusion Constructs

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Study Design: Controlled Laboratory Study

Objective: To compare multilevel posterior cervical fusion (PCF) constructs stopping at C7, T1, and T2 under cyclic load to determine the range of motion (ROM) between the lowest instrumented level and lowest instrumented-adjacent level (LIV-1).

Summary of Background Data: PCF is a mainstay of treatment for various cervical spine conditions. The transition between the flexible cervical spine and rigid thoracic spine can lead to construct failure at the cervicothoracic junction. There is little evidence to determine the most appropriate level at which to stop a multilevel PCF.

Methods: Fifteen human cadaveric cervicothoracic spines were randomly assigned to 1 of 3 treatment groups: PCF stopping at C7, T1, or T2. Specimens were tested in their native state, following a simulated PCF, and after cyclic loading. Specimens were loaded in flexion-extension), lateral bending, and axial rotation. Three-dimensional kinematics were recorded to evaluate ROM.

Results: The C7 group had greater flexion-extension motion than the T1 and T2 groups following instrumentation (10.17 ± 0.83 degree vs. 2.77 ± 1.66 degree and 1.06 ± 0.55 degree, P <0.001), and after cyclic loading (10.42 ± 2.30 degree vs. 2.47 ± 0.64 degree and 1.99 ± 1.23 degree, $P<0.001$). There was no significant difference between the T1 and T2 groups. The C7 group had greater lateral bending ROM than both thoracic groups after instrumentation (8.81 ± 3.44 degree vs. 3.51 ± 2.52 degree, $P=0.013$ and 1.99 ± 1.99 degree, $P=0.003$) and after cyclic loading. The C7 group had greater axial rotation motion than the thoracic groups (4.46 ± 2.27 degree vs. 1.26 ± 0.69 degree, $P=0.010$; and 0.73 ± 0.74 degree, $P=0.003$) following cyclic loading.

Conclusion: Motion at the cervicothoracic junction is significantly greater when a multilevel PCF stops at C7 rather than T1 or T2. This is likely attributable to the transition from a flexible cervical spine to a rigid thoracic spine. Although this does not account for in vivo fusion, surgeons should consider extending multilevel PCF constructs to T1 when feasible.

Level of Evidence: Not applicable.

Key Words: cervicothoracic junction, upper thoracic spine, posterior fusion, cervical fusion, biomechanical, distal junctional kyphosis, adjacent segment disease

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Posterior cervical spine fusion (PCF) is an effective treatment for a variety of cervical spine pathologies.[1,2] Complications and the need for revision surgery following multilevel PCF are not infrequent.[3–5] Infection rates can exceed 10%, and blood loss can be considerable, particularly in cases of trauma or a greater number of fused levels.[6–9] The cervicothoracic junction also presents unique anatomic and biomechanical challenges that surgeons must consider when constructs extend to this region.[3,10] The yearly incidence of clinically significant adjacent segment disease (ASD) following cervical fusion ranges from 1.6% to 4.2%.[11] The increased motion seen at adjacent spinal levels following multilevel fusion may explain this high rate of adjacent segment pathology.[11,12] The transition from the flexible cervical spine to the more rigid thoracic spine also has the potential to lead to

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construct failure at the cervicothoracic junction.[3] Distal junctional kyphosis, or loss of alignment 1 to 2 levels distal to the most caudal instrumented vertebrae, occurs at this area of instability in up to 23.8% of patients treated with multilevel PCF.[13] Distal junctional kyphosis is associated with pain, deformity, and the need for reoperation.[14,15]

Controversy remains regarding how caudal to extend a multilevel PCF construct. From a clinical perspective, conflicting outcomes have been reported between multilevel constructs ending at C7 and those crossing the cervicothoracic junction.[4–7,16–20] A retrospective review demonstrated constructs ending at C7 are over 2 times more likely to require a revision than constructs ending at T1 at a mean follow-up of over 4 years.[4] This finding is further supported by a systematic review and meta-analysis that showed higher fusion rates and lower reoperation rates when the cervicothoracic junction is crossed in over 500 patients who underwent multilevel PCF.[18] A separate systematic review and meta-analysis showed higher rates of ASD and reoperation rate when the cervicothoracic junction is not crossed in multilevel PCF.[9] Conversely, several recent retrospective reviews have shown no difference in reoperation rates between multilevel PCF ending in the lower cervical versus upper thoracic spine.[16,17,21] This conflicting literature demonstrates a lack of clear indications for crossing the cervicothoracic junction with multilevel PCF. To date, no biomechanical study has evaluated the range of motion (ROM) experienced at the lowest instrumented-adjacent vertebral level (LIV-1) after cyclic loading. The purpose of this study is to understand the biomechanical profile of the cervicothoracic junction after multilevel PCF stopping at C7, T1, and T2. Our hypothesis was that constructs with the lowest instrumented vertebral level (LIV) at C7 would generate greater motion at LIV-1 as compared with constructs that crossed the cervicothoracic junction.

MATERIALS AND METHODS

Specimens

Fifteen fresh-frozen human cadaveric cervicothoracic spines (C1–T5) were procured and stored at −30°C. The specimens were screened for deformities, evidence of prior injuries, and instrumentation. The specimens were thoroughly cleaned of nonstructural soft tissue and dorsal musculature, preserving the ligaments, joint articulations, transverse processes, and intervertebral disks. Each specimen was randomly assigned to 1 of 3 treatment groups: PCF stopping at C7, T1, and T2. Specimens were then disarticulated into functional spine units (FSUs) according to their treatment group: C4–T2, C5–T3, and C6–T4, respectively. Most cephalad and caudad vertebrae were potted at ~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. Screws were inserted into potting material to anchor the vertebral bodies. Space was left in the cephalad pot for embedding fusion rods.

Experimental Design and Biomechanical Testing

After disarticulation into FSUs, the ROM of the intact, uninstrumented specimens was evaluated first. Each FSU was mounted on a servohydraulic material testing system augmented with a Spine Test Fixture (MTS 858 Mini Bionix II, MTS Systems Corp., Eden Prairie, MN). 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 a custom spine gimbal for applying bending rotations and torques. Infrared rigid body markers (Optotrak Certus, Northern Digital, Inc., Waterloo, Ontario, CA) were attached to the ventral aspect of the cephalad and caudad vertebral body at the level of interest to record 3-dimensional vertebral kinematics (Fig. 1). For FSUs randomized to undergo multilevel PCF stopping at C7, T1, and T2; ROM was recorded at the LIV-1 (C7–T1, T1–T2, and T2–T3 levels, respectively). To evaluate ROM, each FSU was nondestructively bent in 3 different directions, flexion-extension (FE), right and left lateral bending (LB), and right-left axial rotation (AR). Specimens were bent under angular control at a 0.5 degree/s rate with a constant 10 N axial compression preload throughout and until the predetermined 1.5 Nm torque limit was reached. Bending in each direction was repeated 3 times to minimize creep; ROM at the LIV-1 was recorded during the third repetition, as has previously been reported.[22] Specimens were sprayed with saline regularly throughout testing to prevent desiccation.[23]

Once the intact, uninstrumented ROMs were evaluated, FSUs were instrumented according to their treatment group. Each FSU was then re-potted with the cephalad aspect of the rods incorporated into the potting to simulate a multilevel PCF construct.[24] The ROM at LIV-1 was again evaluated for each specimen using the same testing procedure described above. The instrumented FSU were subjected to cyclic loading in flexion-extension (±1.5 Nm) at 0.1 Hz rate for 1000 cycles. ROMs were evaluated for a final time after cyclic loading using the same testing procedure.

Surgical Treatment

Specimens were instrumented by 1 of 2 fellowship-trained spine surgeons from C5–C7, C7–T1, or T1–T2, depending on their treatment group. In the C5–C7 group, lateral mass screws were used at C5 and pedicle screws at C7. The C6 level was not instrumented to allow adequate space for C7 pedicle screw insertion. Once the appropriate soft tissues were removed through sharp and blunt dissection, lateral mass screw start points at C5 were prepared with a 3 mm high-speed burr (Medtronic, Fridley, MN) and drilled to a 12 mm depth with a 2 mm hand drill. Screw tracts were then tapped with a 3.5 mm tap and a 14×3.5 mm polyaxial screw (Mountaineer OCT Spinal System, DePuy Spine, Raynham, MA) was inserted. In the FSUs instrumented from C7–T1 and T1–T2, pedicle screws were used for fixation at the C7, T1, and T2 levels. Start points were identified and prepared with the 3 mm high-speed burr and an awl. Screw depth was measured

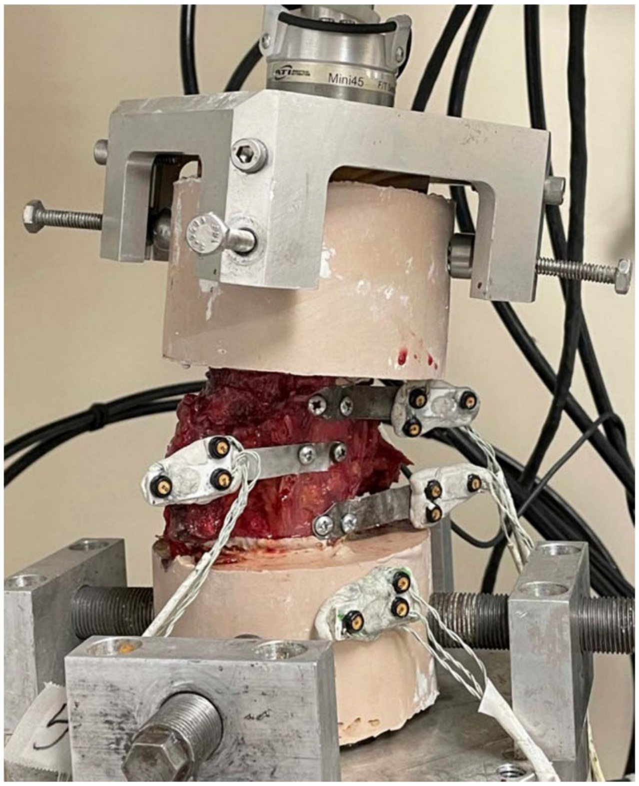

FIGURE 1. An intact specimen loaded onto servohydraulic materials testing system with infrared rigid body markers attached to the ventral aspect of each vertebrae and potting material for recording of three-dimensional kinematics.

using a blunt-tip probe and ruler and an appropriate length 4 mm polyaxial pedicle screws (Mountaineer OCT Spinal System, DePuy Spine, Raynham, MA) were placed. Screw placement was confirmed through fluoroscopy and then 3.5 mm titanium rods were contoured and secured with set screws. Rods were then incorporated into the cephalad-sided potting to simulate a multilevel fusion construct (Fig. 2).

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 subsequently translated to vertebral ROMs in FE, LB, and AR.

Statistical Analysis

ROM in degrees for FE, LB, and AR was recorded from intact specimens before cyclic loading and after being subjected to cyclic loading. Measurements between the 3 groups were compared using 2-way mixed analysis of variance (ANOVA) followed by Bonferroni-adjusted post-hoc pairwise comparisons ($P < 0.05$). All statistical analyses were performed using R (v4.0.2, Vienna, Austria) in RStudio (v1.3, Rstudio, Inc., Boston, MA) using the rstatix packages.

RESULTS

Flexion-Extension

In the intact, uninstrumented specimens, the mean LIV-1 FE ROM in the C7, T1, and T2 groups was 0.94 ± 1.50 degree, 2.12 ± 0.88 degree, and 1.06 ± 0.48 degree, respectively (Fig. 3A). There was no significant difference between groups (C7 vs. T1, $P = 0.63$; C7 vs. T2, $P = 1.00$; T1 vs. T2, $P = 0.67$). After instrumentation and before being subjected to cyclic loading, there was greater motion in the C7 group (10.17 ± 0.83 degree) compared with both the T1 (2.77 ± 1.66 degree, $P < 0.001$) and T2 (1.06 ± 0.55 degree, $P < 0.001$) groups. There was no significant difference between the T1 and T2 groups ($P = 0.16$). After cyclic loading, there was also greater motion in the C7 group (10.42 ± 2.30 degree) compared with the T1 (2.47 ± 0.64 degree, $P < 0.001$) and T2 (1.99 ± 1.23 degree, $P < 0.001$) groups. There was no difference in post-cyclic loading between the T1 vs. T2 groups ($P = 1.00$).

Lateral Bending

LB ROM for each treatment group are shown in Figure 3B. For intact, uninstrumented specimens, the mean LIV-1 LB ROM in the C7, T1, and T2 groups was 8.77 ± 2.52 degree, 2.41 ± 1.76 degree, and 2.49 ± 1.78 degree, respectively. The intact C7 group had significantly greater motion than both the T1 ($P = 0.004$) and T2 ($P = 0.005$) groups. There was no difference in motion between the T1 and T2 groups ($P = 1.00$). After instrumentation and before cyclic loading, there was significantly greater motion in the C7 group (8.81 ± 3.44 degree) than in the T1 (3.51 ± 2.52 degree, $P = 0.02$) and T2 (2.00 ± 2.00 degree, $P = 0.002$) groups, with no difference between the T1 and T2 groups ($P = 1.00$). After being subjected to cyclic loading, the C7 group exhibited greater motion (8.51 ± 3.24 degree) than the T1 (2.89 ± 2.04 degree, $P = 0.01$) and T2 (1.83 ± 1.84 degree, $P = 0.003$) groups. There remained no difference between the T1 and T2 groups ($P = 1.00$).

Axial Rotation

In the uninstrumented specimens, the mean AR ROM at LIV-1 in the C7, T1, and T2 groups was 1.91 ± 1.10 degree, 1.55 ± 1.71 degree, and 1.16 ± 1.19 degree, respectively. There was no significant difference between each group ($P = 1.00$). After instrumentation, there was significantly greater motion in the C7 group (3.35 ± 2.25 degree) than the T2 group (0.60 ± 0.39 degree, $P = 0.03$). There was decreased motion in the T1 group (1.13 ± 0.41 degree) compared with the C7 group that did not reach statistical significance ($P = 0.10$). No difference was seen between the T1 and T2 groups ($P = 1.00$). After being subjected to cyclic loading, there was significantly greater motion in the C7 group (4.46 ± 2.27 degree) than in the T1 (1.26 ± 0.69 degree, $P = 0.01$) and T2 (0.73 ± 0.74 degree, $P = 0.003$) groups. There was no difference between the T1 and T2 groups ($P = 1.00$). ROM in AR for each treatment group is shown in Figure 3C.

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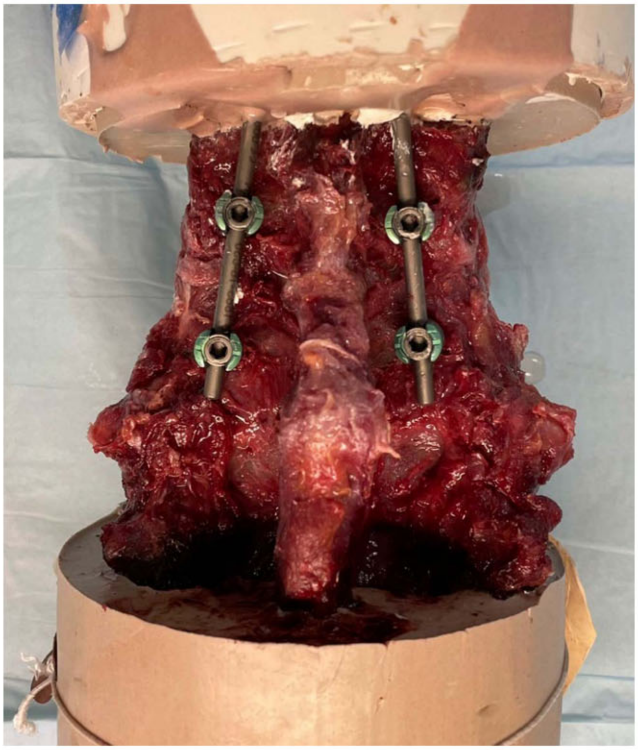

FIGURE 2. Instrumented specimen with the cephalad aspect of rods incorporated into potting material to simulate a long posterior cervical fusion construct.

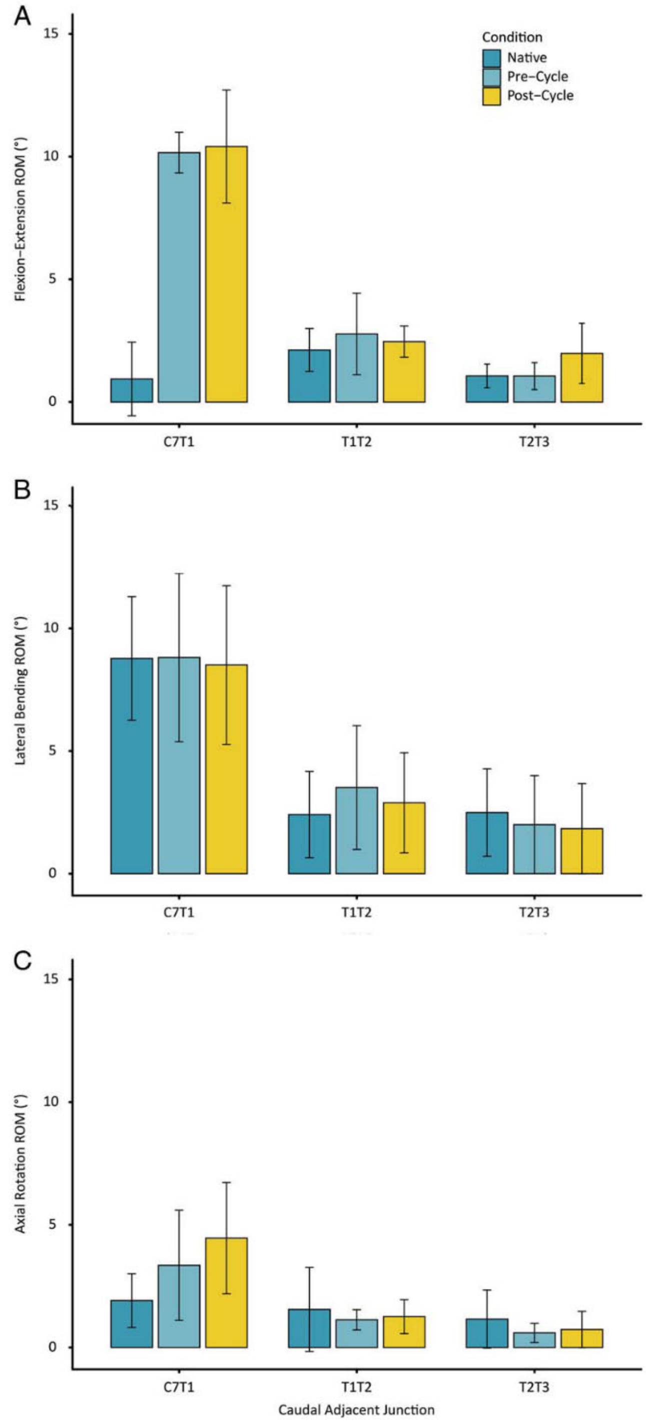

FIGURE 3. A–C. Summaries of the range of motion result in flexion-extension (A), right and left lateral bending (B), and right-left axial rotation (C) in intact specimens before cyclic loading and after being subjected to cyclic loading in the C7, T1, and T2 groups. ROM indicates range of motion.

DISCUSSION

The purpose of this study was to compare ROM at the LIV-1 of multilevel PCF constructs under cyclic load ending at C7, T1, and T2. Our results demonstrate significantly increased motion at the cervicothoracic junction when a multilevel PCF stops at C7 rather than at T1 or T2. These findings held true across 3 planes of motion and both before and following cyclic loading. To our knowledge, this is the first biomechanical study that directly compared the motion of PCF constructs ending at the C7, T1, and T2 levels of both pre-cyclic and post-cyclic load. A prior biomechanical study examining PCF constructs under cyclic load utilized outdated posterior plate and plate-hook constructs rather than more modern screw-rod constructs, as in our study.[25] Of the few studies that examine the biomechanics specifically at the cervicothoracic junction, they often involve simulated low cervical spine injury when the junction must be spanned.[26,27] Our biomechanical data suggests that constructs ending at C7 are prone to increased motion when compared with constructs ending at T1 or T2.

Prior clinical studies have shown conflicting results when comparing the extent of multilevel PCF constructs.[4–7,16–20] Osterhoff et al[5] showed no difference in radiographic outcomes in a retrospective analysis comparing posterior constructs ending at C7 versus T1 and T2. However, the C7 group had significantly higher rates of secondary intervention due to symptomatic lower adjacent segment pathology or implant failure.[5] Schroeder et al[4] and Ibaseta et al[19] similarly showed a higher rate of revision with fusion constructs ending at C7 when compared with those crossing the cervicothoracic junction. A meta-analysis including some of the above studies dem-

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onstrated lower odds (OR, 0.42) for all-cause revisions when the cervicothoracic junction is crossed compared with when it is not crossed.[18] In contrast, others have shown similar clinical results and revision rates for ASD regardless of the caudal extent of a PCF construct.[6,7,16,17,20] Guppy et al[17] found no significant difference with multilevel PCF constructs ending at C7 versus T1/T2 at an average follow-up of 4.6 years. The morbidity of the extension of a PCF into the thoracic spine is also unclear. Whereas some have reported increased operative morbidity associated with extension into the upper thoracic spine,[6,7,9,20] others report similar blood loss, operative time, and length of stay regardless of extension past the cervicothoracic junction.[19]

Prior biomechanical studies evaluating the cervicothoracic junction have reported similar results to those of our study. Kretzer et al[28] showed decreased motion and intradiscal pressure at C7–T1 when fusion constructs extended into the thoracic spine following C3–C7 laminectomies. Our findings are also consistent with another biomechanical study that showed increased motion in cervical spinal segments adjacent to fusions. The most significant increase in motion occurred in the level immediately caudal to the fusion construct during extension and the increased motion coincided with greater intradiscal pressures at levels adjacent to the fusion construct.[29] In a separate biomechanical comparison of intradiscal pressures across multilevel cervical and cervicothoracic fusion constructs, it has been suggested that crossing the cervicothoracic junction may lead to a decrease in intradiscal pressure at the T2–T3 level.[30]

Greater motion at particular spinal levels may contribute to increased intradiscal pressures at the level of interest.[29,30] Age-related changes to the biological and structural properties of intervertebral disks are well characterized.[31] Changes known to occur in the degenerative intervertebral disk have also been observed in response to high compressive forces in an animal model.[32] The greater motion observed at the LIV-1 when our constructs did not cross the cervicothoracic junction may offer a mechanical explanation for some of these biological changes that are thought to precede ASD and construct failure. The results of this study suggest that the extension of a multilevel PCF construct into the upper thoracic spine limits motion across the cervicothoracic junction. In conjunction with much of the available clinical data,[4,5,19,20] a strong argument can be made to extend multilevel PCF constructs into the upper thoracic spine. Extension of these constructs across the cervicothoracic junction may decrease the high rates of ASD.[13]

This study is not without its limitations, many inherent to any biomechanical study that employs a cadaveric model. This study does not take into account the bony fusion that occurs after instrumentation in vivo. Cyclic loading protocols are designed to simulate the stresses placed upon a construct before bony fusion. If fusion does not occur in 6–8 weeks, constructs are at increased risk for failure.[33,34] Prior literature suggests that 18,000 cycles are needed to simulate the time required for fusion to occur.[33–35] Our cyclic loading protocol was limited to 1000 cycles of loading, given the time required when cycling at a rate of 0.1 Hz. Future studies would increase the rate of cyclic loading to more expeditiously reach 18,000 cycles. A second limitation of this study relates to the lack of anterior instrumentation in any of our specimens. It has been hypothesized that the weakness of posterior musculature following PCF and lack of anterior structural support contributes to some of the differences in adjacent segment pathology seen following anterior versus posterior fusions.[4] While anterior cervical fusion remains the most common in the United States, PCF still accounts for ~7.5% of the cervical spine fusions.[36] The findings presented in this study remain applicable to a significant number of surgical cases with the potential to guide surgeons questioning whether to span the cervicothoracic junction. Future biomechanical studies should investigate intradiscal pressures across the lowest instrumented and lowest instrumented-adjacent levels of varying constructs.

CONCLUSION

Motion at the lowest instrumented-adjacent level is significantly greater when a multilevel PCF stops at C7 rather than at T1 or T2. Crossing the cervicothoracic junction in a multilevel PCF construct can decrease motion at this level and potentially lower rates of ASD, as well as the rate of revision surgery. Although this biomechanical study does not account for in vivo fusion, surgeons should consider extending multilevel PCF constructs to T1 when feasible.

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