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Basic Science

Supplemental rods are needed to maximally reduce rod strain across the lumbosacral junction with TLIF but not ALIF in long constructs

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Abstract

BACKGROUND CONTEXT: Rod fracture at the lumbosacral (LS) junction remains challenging in long segment fusions and likely stems from increased LS strain. Reduction of LS instrumentation strain may help reduce fracture rates.

PURPOSE: The goal of this investigation was to assess the effect of supplemental posterior 4-rod (4R) construction on LS stability and rod strain compared with standard 2-rod (2R) construction in a long segment fusion model.

STUDY DESIGN/SETTING: Cadaveric biomechanical study.

OUTCOME MEASURES: Range of motion (ROM), rod strain, and sacral screw (SS) bending moments during flexion, extension, compression, lateral bending, and axial rotation.

METHODS: Standard nondestructive flexibility tests (7.5 Nm) were performed on 14 cadaveric specimens (L1-ilium) to assess ROM stability, rod strain, and SS bending moment of a supplemental 4R construction versus standard 2R construction. Specimens were equally divided into L5-S1 anterior lumbar interbody fusion (ALIF) or L5-S1 transforaminal lumbar interbody fusion (TLIF) groups. Three conditions were tested in each group: (1) no lumbar interbody fusion (No LIF)+2R, (2) ALIF or TLIF+2R, and (3) ALIF or TLIF+4R. Data were analyzed using repeated measures analysis of variance (ANOVA) or ANOVA.

RESULTS: No differences were observed between groups 1 and 2 for age, sex, bone mineral density, or baseline ROM ($p>.09$). Overall, TLIF+2R demonstrated greater ROM than ALIF+4R in extension (p=003), with greater rod strain in flexion, extension, and compression ($p<.001$), and greater SS in compression and AR ($p<.04$). Compared with TLIF+2R, TLIF+4R resulted in reduced rod strain in flexion, extension, compression, and LB ($p<.04$), as well as SS in AR ($p<.001$). The TLIF+4R yielded biomechanics comparable to ALIF+2R in ROM and rod strain

FDA device/drug status: Not applicable.

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but SS inflexion, extension, compression, and AR remained elevated (p<001). The ALIF+4R did not significantly improve ROM, rod strain, or SS (p>.11).
CONCLUSIONS: The use of ALIF and adding accessory rods with TLIF significantly reduced LS rod strain in a long segment cadaveric model with iliac fixation.
CLINICAL SIGNIFICANCE: Reducing strain could decrease the risk of failure associated with long segment fixation.

Keywords: Bending moment; Compression; Extension; Failure; Fixation; Flexion; Instrumentation; Lateral bending; Range of motion; Screw

Introduction

Spinal deformity surgery presents a unique biomechanical and clinical challenge. Surgical constructs must often span multiple levels to achieve adequate correction, in certain circumstances necessitating fixation across the lumbosacral junction. The lumbosacral junction is a biomechanically demanding region of the spine subject to loads as high as 11 times the body weight [1]. The resulting surgical constructs are subject to significant mechanical strain that leads to a high risk of instrumentation failure at the lumbosacral junction [2−7].

Reductions in lumbosacral strain are associated with improved fusion rates and a lower incidence of instrumentation failure [8]. A common augmentation technique involves iliac fixation, which protects against sacral screw (SS) failure but may lead to increased rod strain caused by the longer lever arm [4,9]. Surgical strategies involving structural anterior column support with anterior or posterior interbody arthrodesis provide improved stability and decreased strain [4,10,11]. Rod fracture remains the leading cause of revision surgery in adult spinal deformity. The rate of rod fracture in open posterior, adult spinal deformity−correction is as high as 18.5% [6,12]. Clinical and biomechanical studies indicate that use of supplemental rods across high-stress sites such as three column osteotomies (3CO) leads to reduced rod strain and mitigates the risk of instrumentation failure [13−19]. However, no prior studies have investigated the use of supplemental rods across the lumbosacral junction or the interplay between interbody choice (anterior lumbar interbody fusion [ALIF], or transforaminal lumbar interbody fusion [TLIF]) and rod density.

The goal of this investigation was to assess the effect of supplemental posterior 4-rod (4R) construction on lumbosacral stability and rod strain compared with standard 2-rod (2R) construction in a long segment fusion with anterior column support (ALIF or TLIF) and pelvic fixation. We hypothesized that the increased rod density with 4R fixation across the lumbosacral junction would provide greater stability, reduce rod strain, and reduce SS strain in both ALIF and TLIF conditions.

Methods

Specimens

Fourteen human cadaveric L1-ilium specimens were studied in 2 groups. The mean donor age was 51.6±7.4 years; 9 donors were male, and 5 were female (Table 1). By screening the records from the cadaver supplier, reviewing plain film radiographs, and directly inspecting the specimens, we ensured that no specimen had obvious pathology that might affect biomechanical testing. Dual-energy X-ray absorptiometry was performed on each specimen at L4 to assess the bone mineral density (BMD, g/cm^2). Specimens were divided into 2 groups following intact testing based on statistical comparability of age, sex, BMD, and range of motion across L1-Ilium and L5-S1.

Specimens were wrapped and stored at −20˚C until tested. Specimens were thawed in normal saline at 21˚C and cleaned of muscle tissue while keeping intact all ligaments,

Table 1
Donor demographic and DEXA data

Specimen no.	Sex	Donor age (years)	DEXA (t-score)
Group 1 (ALIF)			
1	F	49	1.156
2	M	34	1.066
3	M	52	0.76
4	F	55	1.202
5	M	45	0.86
6	M	60	0.668
7	F	43	0.633
Mean±SD		48.2±8.6	0.91±0.2
Group 2 (TLIF)			
8	F	53	0.633
9	F	53	0.744
10	M	50	1.118
11	M	53	0.68
12	M	55	0.949
13	M	64	0.568
14	M	57	0.68
Mean±SD		55±4.5	0.76±0.2

ALIF, anterior lumbar interbody fusion; DEXA, dual-energy x-ray absorptiometry; TLIF, transforaminal lumbar interbody fusion.

joint capsules, and discs. For testing, the exposed end plate and facet articulations of the ilia and L1 vertebral bodies were reinforced with household wood screws; screw heads and part of the vertebral body were embedded in a cylindrical fixture using fast-curing resin (Smooth-Cast, Smooth-On, Inc., Easton, PA) and attached to the base of the testing apparatus.

In all cases, polyaxial pedicle screws with a cobalt chrome head and titanium alloy shaft (Ti-6A1-4V) were used (NuVasive; L2-5: 6.5×45−55 mm, S1: 7.5×55 mm, Ilium: 9.5×80 mm) from L2 to Ilium. Two 5.5-mm diameter cobalt chrome rods were contoured bilaterally to fit the screw heads to minimize need for reduction technique for the standard 2R construction; offset connectors between the iliac screws and the rod were used. For the supplemental 4R construction, bilateral accessory rods were placed medial to the primary rod using side-to-side connectors spanning between the L3/4 and S1/Ilium levels (Fig. 1). Once placed and locked, primary rods remained in place for all instrumented conditions.

For group 1, an ALIF construct was placed at L5-S1, consisting of an anteriorly placed titanium interbody implant (BASE Interfixated Titanium System, NuVasive, San Diego, CA) with 3 5.0×25-mm screws (1 in L5, 2 in S1); interbody implants were of standard width (28 mm) and varied in lordosis (15°−20°) according to the dimensions of the specimen to fit into the disc space without a change of alignment.

For group 2, a left transforaminal interbody (TLIF; Anterior TLIF Spinal System, NuVasive) was placed, with a height of 10 to 12 mm, according to the specimen and were of standard length (30 mm). Implants were inserted using standard tools and surgical techniques at the spine surgeon's discretion. For each specimen, lateral and

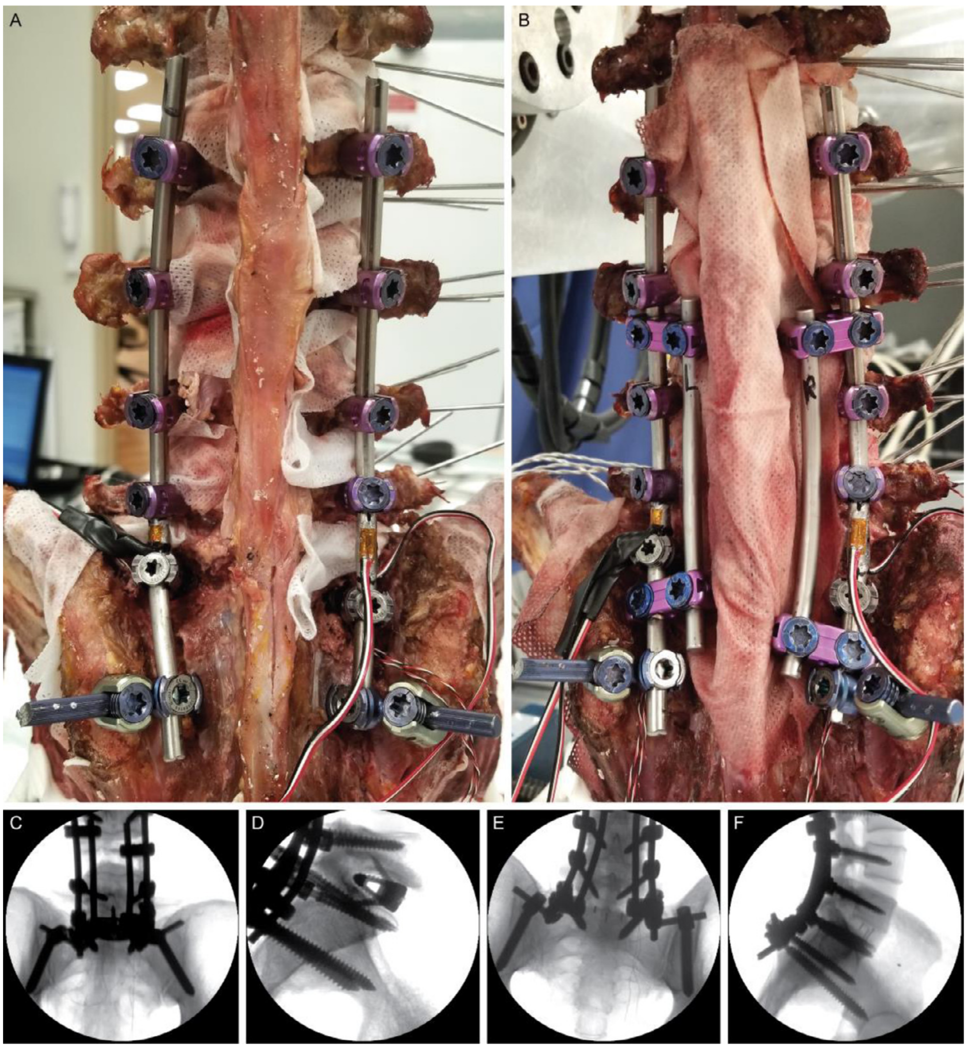

Fig. 1. Two and 4R configurations of an L2-Ilium construct. (A) Demonstrates a 2R construct, with strain gauges attached between L5/S1, and bilateral S1 screws. (B) Demonstrates a 4R construct with an accessory rod attached with a side-to-side connector between L3/4 and S1/Ilium. Anteroposterior and lateral radiographs of anterior lumbar interbody fusion (C, D) and transforaminal lumbar interbody (E, F) constructs. Used with permission from (Institution blinded for review). 4R, 4-rod construction; 2R, 2-rod construction.

anteroposterior fluoroscopy was used to verify correct screw
trajectory and implant placement.

Testing conditions

Specimens were tested by groups as follows:
Group 1 (ALIF):
(1) Intact
(2) No lumbar interbody fusion (LIF)+2R
(3) ALIF+2R
(4) ALIF+4R

Group 2 (TLIF):
(1) Intact
(2) No LIF+2R
(3) TLIF+2R
(4) TLIF+4R

In each group, the order of 3 and 4 was randomized.

Biomechanical testing

Specimens were rigidly fixed caudally to the testing frame with unconstrained lateral translation between left and right ilia and were fixed cranially to the end effector of a robotically controlled testing system [20]. In all the conditions that were tested, the specimens were studied using pure moment flexibility tests. Maximum loads of 7.5 Nm were applied continuously at an approximate 1.2°/s global rotation rate to induce flexion, extension, and lateral bending (LB), axial rotation (AR). After the bending tests, specimens were loaded in pure compression (400 N) at an approximate rate of 30 N/s. Two preconditioning cycles were applied to allow for creep in each loading direction to ensure appropriate settling at the instrumentation-bone interface and to improve the reproducibility of results.

Three-dimensional (3D) specimen motion in response to applied loads during flexibility testing was determined automatically at 2 Hz using the Optotrak 3020 system (Northern Digital, Inc., Waterloo, Ontario, Canada). This system stereophotogrammetrically measures the 3D displacement of infrared-emitting markers that are rigidly attached in a noncollinear arrangement to each vertebra. Custom software converts the marker coordinates to angles about each anatomical axis in terms of the coordinate system of the motion segment [21]. Spine angles were calculated using a technique that provides appropriate results for describing 3D spinal motion; values were rounded to the nearest 0.1° [22].

Sets of SSs (two 7.5×55 mm and two 8.5×55 mm) were instrumented with uni-axial strain gauges (EA-06-031CE-350, Vishay Micro-Measurements, Raleigh, NC) oriented in line with the long axis of each screw. In each case, a total of 4 gauges were placed circumferentially near the screw head with opposing gauges wired together in ½-bridge configurations. Calibration procedures were performed on each screw before implantation to obtain strain versus screw bending moment relationships [23]. Posterior rods were instrumented with 2 uni-axial strain gauges (CEA-06-062UW-350/P2, Vishay Micro-Measurements) midway between L5 and S1, with the gauges facing anteriorly and posteriorly on each specimen, respectively. Unlike the SSs, the instrumented rods were not calibrated. The strain on the SSs and posterior rods during specimen loading were recorded at 10 Hz using the StrainSmart data acquisition system (Vishay Micro-Measurements, Raleigh, NC). Biplanar SS bending moments were used to calculate resultant screw bending moments. The resultant SS bending moments and rod strains at peak loads were used for analyses in each case. Because there were no statistical differences between the right and left side strain outputs during flexion, extension, and compression, or ipsilateral and contralateral sides during right and left LB and AR, (SS p>.38, or rod p>.26), data were grouped and analyzed accordingly.

Analysis

Statistical comparisons between group 1 and group 2 specimens were performed using standard *t* tests to determine similarity in age, sex, BMD, and ROM. Values of ROM across L5/S1, rod strain at L5/S1, and SS were compared within each group and in between groups. To help minimize variability outcomes among specimens of different inherent flexibility, raw ROM values were normalized by dividing the ROM in the instrumented condition by its corresponding ROM in the intact condition; intragroup variability was assessed using 1-way repeated measures-ANOVA (eg, within group 1), and intergroup variability (eg, group 1 vs. group 2) were analyzed using 1-way ANOVA, followed by paired Holm-Šidák tests, to determine whether outcomes among conditions were significantly different. Statistical significance was set at p<.05.

RESULTS

No significant differences were observed between groups 1 and 2 for age (p=.09), sex (p>.99), BMD (p=.561), baseline L1-Pelvis ROM (p=.62), or baseline L5-Sacrum ROM (p=.71).

Analysis of motion

A summary of mean raw ROM values at L5/S1 are provided in Table 2, and normalized data are presented in Fig. 2. All LIF conditions demonstrated lower flexion ROM than no LIF+2R (p≤.04).The 4R construct did not provide additional stability for TLIF (p=.14) or ALIF (p=.27). There was no significant difference between ALIF and TLIF constructs (p=.20) for flexion.

All LIF conditions except TLIF+2R (p=.24) demonstrated significantly lower extension ROM than no LIF+2R (p≤.01). The 4R construct did not provide additional stability for

Table 2
Raw values of range of motion (ROM) across Lumbosacral junction

	Direction (degrees)			Lateral bending (degrees)		Axial rotation (degrees)	
Group, construct	Flexion	Extension	Compression (degrees)	Left	Right	Left	Right
Group 1, ALIF							
Intact	5.67±2.29	−4.60±1.35	2.8±1.8	−2.78±1.23	2.10±1.62	1.35±0.72	−1.07±0.78
No LIF+2R	0.23±0.10	−0.3±0.15	0.33±0.11	−0.05±0.08	0.12±0.10	0.30±0.17	−0.42±0.24
ALIF+2R	0.00±0.06	−0.03±0.05	0.02±0.08	−0.02±0.08	0.08±0.08	0.13±0.14	−0.2±0.11
ALIF+4R	0.05±0.10	−0.02±0.04	0.05±0.10	−0.03±0.08	0.12±0.1	0.12±0.04	−0.1±0.13
Group 2, TLIF							
Intact	6.04±3.94	−5.47±2.59	3.6±1.9	−3.13±1.76	2.50±1.70	0.83±0.68	−0.93±0.53
No LIF+2R	0.23±0.15	−0.2±0.18	0.37±0.27	−0.07±0.05	0.12±0.10	0.33±0.20	−0.38±0.11
TLIF+2R	0.08±0.08	−0.13±0.08	0.1±0.11	−0.15±0.05	0.13±0.05	0.28±0.12	−0.38±0.17
TLIF+4R	0.02±0.04	−0.05±0.05	0.08±0.13	−0.12±0.08	0.07±0.16	0.27±0.08	−0.31±0.11

2R, 2-rod construction; 4R, 4-rod construction; ALIF, anterior lumbar interbody fusion; LIF, lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.
Data are mean±SD.
Intact condition not shown.

either TLIF (p=.08) or ALIF (p=.47). ALIF+4R demonstrated lower ROM than TLIF+2R (p=.03); there were no other significant difference between ALIF and TLIF constructs (p≥.18) for extension.

All LIF conditions demonstrated lower ROM for compression compared with no LIF+2R (p≤.044); the 4R construct did not provide additional stability for either TLIF (p=.83) or ALIF (p=.39). There was no significant difference between ALIF and TLIF constructs (p=.39) for compression.

TLIF+2R demonstrated greater LB ROM than no LIF +2R (p=.04) in left LB; all other LIF constructs demonstrated comparable stability to no LIF+2R (p≥.51) in both left and right LB. The 4R construct did not provide additional stability for either TLIF (p=.39) or ALIF (p=.34). There were no significant differences between ALIF and TLIF constructs in right or left LB (p≥.15).

ALIF+4R demonstrated lower AR ROM compared with no LIF+2R in right AR (p=.02). All other LIF constructs demonstrated comparable stability to no LIF+2R (p≥.06) in left and right AR. The 4R construct did not provide additional stability for either TLIF (p≥.61) or ALIF (p≥.23). There were no significant differences between ALIF and TLIF constructs in right or left AR (p≥.11).

Analysis of rod strain

A summary of mean rod strain values is provided in Table 3 and Fig. 3. Overall, the mean rod strain during flexion, extension, and compression was greater with TLIF than with ALIF in all configurations (Table 3, Fig. 3), with statistical significance for 2R during flexion, extension, and compression (p<.001), and with 4R during flexion (p=.03), compression (p=.009), but not during extension (p=.05). Compared with NoLIF+2R, ALIF+2R significantly decreased rod strain during flexion, extension, and compression (Fig. 3, p≤.01) whereas TLIF+2R did not (Fig. 3, p>.2). Rod strains significantly decreased with TLIF+4R versus TLIF+2R during both flexion, extension, and compression (Fig. 3, p≤.02) whereas there were no differences between ALIF+4R and ALIF+2R during flexion, extension, or compression (Fig. 3, p≥.2). Rod strain with TLIF+4R was comparable to that with ALIF+2R during flexion, extension, and compression (Fig. 3, p>.05).

Lateral bending

During LB, the trend for the contralateral side rod (ie, the rod away from the direction of bending) was to bend in extension although the ipsilateral side rod bent in flexion (Fig. 3). Rod strain during LB significantly decreased with ALIF+2R versus NoLIF + 2R on both the ipsilateral and contralateral sides (Fig. 3, p≤.003) whereas the decrease in strain with TLIF+2R versus NoLIF+2R was nonsignificant on either side (Fig. 3, p≥.18). There were no significant differences in rod strain with ALIF+4R versus ALIF+2R on either side (p≥.22), or TLIF+4R versus TLIF+2R on the contralateral side (p=.3). There were no differences in rod strain with ALIF+4R versus TLIF+4R, or ALIF+2R versus TLIF+2R on either side (Fig. 3, p≥.64).

Axial rotation

During AR, the trends for the ipsilateral side rod were to bend in extension and for the contralateral side rod to bend in flexion in all conditions (Fig. 3). Compared with NoLIF +2R, rod strain significantly increased on the contralateral side with both ALIF+2R and ALIF+4R (Fig. 3, p≤.02), and on the ipsi-lateral side with ALIF+2R (Fig. 3, p=.04). The changes in rod strain during AR with TLIF were not statistically significant (Fig. 3, p=.49). Overall, during AR there were no significant differences in sagittal plane rod strain between ALIF and TLIF constructs (p≥.83).

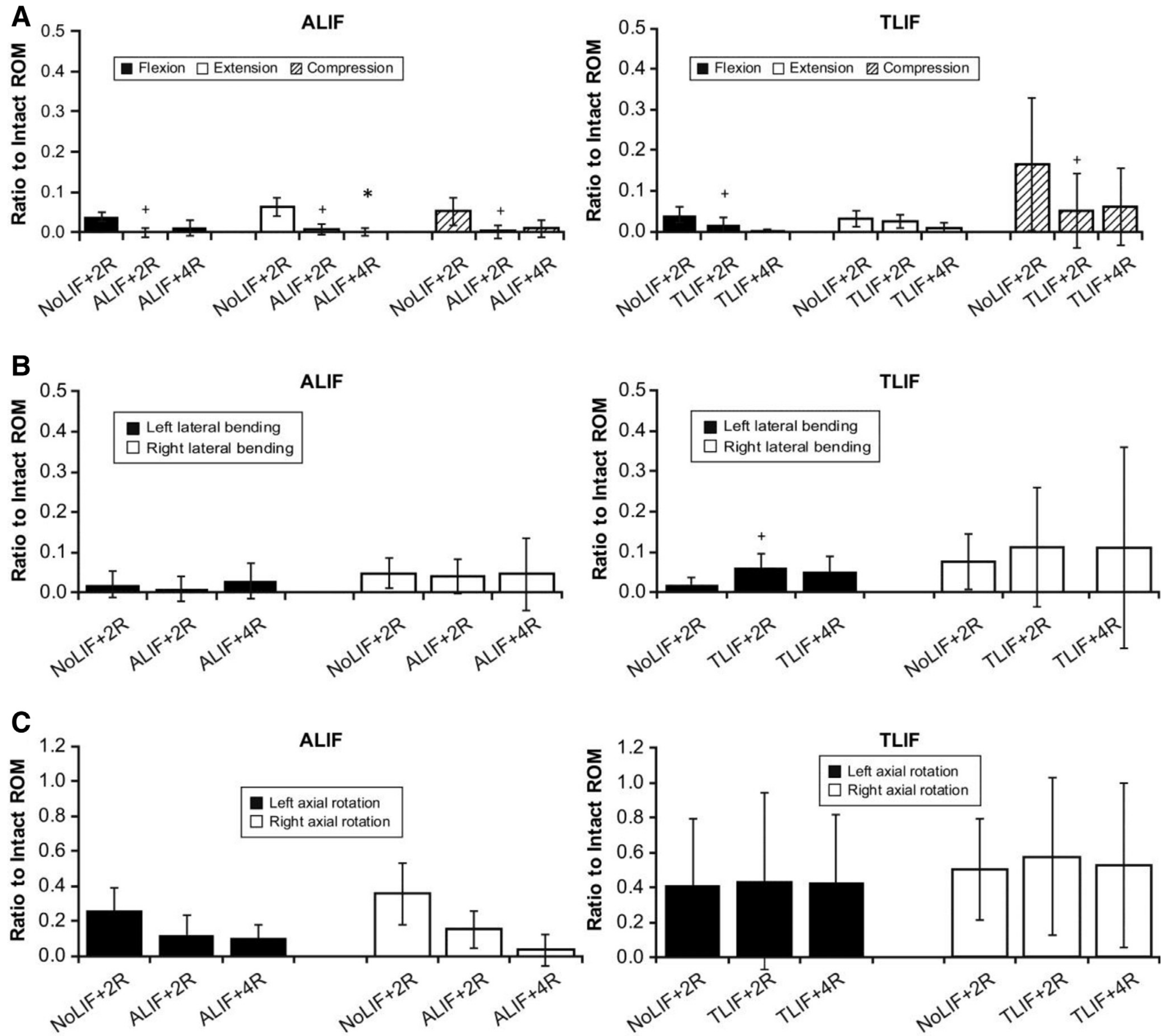

Fig. 2. Normalized ROM stability across ALIF and TLIF constructs. (A) Graphs demonstrate ROM (degrees) across flexion, extension, and compression; (B) left and right lateral bending; (C) left and right axial rotation. #p < .05 for 4R versus 2R. +p < .05 for ALIF or TLIF + 2R versus No LIF + 2R. *p < .05 for comparisons between ALIF and TLIF. Used with permission from [Institution blinded for review]. 2R, 2-rod construction; 4R, 4-rod construction; ROM, range of motion; ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

Table 3
Rod microstrain ($\mu\varepsilon$)

	Direction ($\mu\varepsilon$)			Lateral bending ($\mu\varepsilon$)		Axial rotation ($\mu\varepsilon$)	
Construct	Flexion	Extension	Compression	Ipsilateral	Contralateral	Ipsilateral	Contralateral
No LIF+2R (TLIF)	303±109	−343±118	636±127	51±61	−41±52	−52±103	40±93
TLIF+2R	241±64	−322±97	573±127	31±40	−31±51	−56±68	34±64
TLIF+4R	148±21	−180±33	353±39	25±33	−30±40	−60±49	52±48
No LIF+2R (ALIF)	227±104	−288±137	465±163	64±54	−62±54	−18±83	−4±72
ALIF+2R	108±57	−143±73	215±113	26±35	−39±44	−70±70	57±65
ALIF+4R	72±38	−75±37	157±102	15±36	−17±33	−57±72	49±62

2R, 2-rod construction; 4R, 4-rod construction; ALIF, anterior lumbar interbody fusion; LIF, lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

Data are mean±SD.

Intact condition not shown.

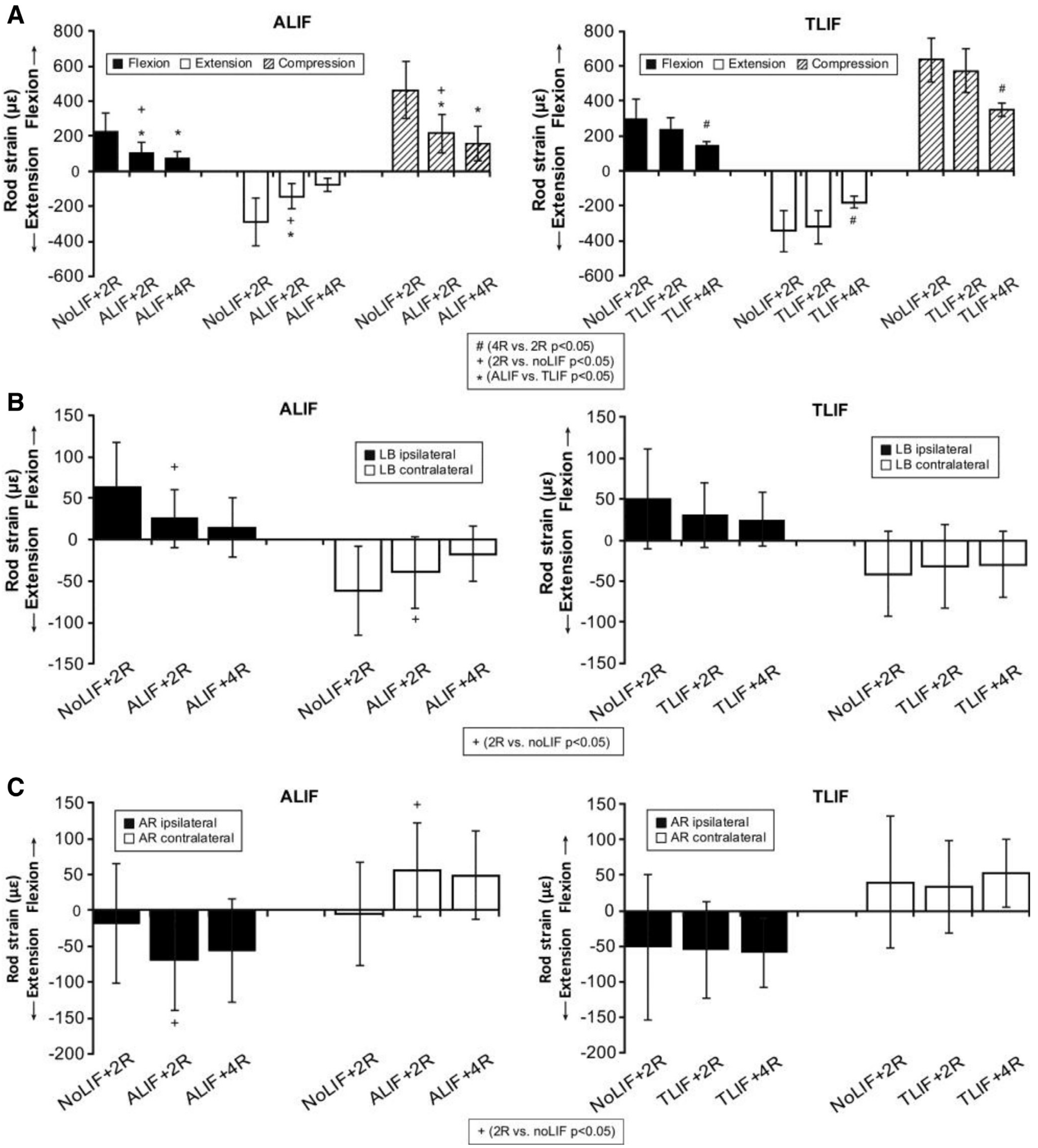

Fig. 3. Rod strain (microstrain, $\mu\varepsilon$) in ALIF and TLIF constructs. (A) Graphs demonstrate rod strain across flexion, extension, and compression; (B) left and right lateral bending; (C) left and right axial rotation. #p < .05 for 4R versus 2R. +p < .05 for ALIF or TLIF + 2R versus No LIF + 2R. *p < .05 for comparisons between ALIF and TLIF. Used with permission from (Institution blinded for review). ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; 2R, 2-rod construction; 4R, 4-rod construction; AR, axial rotation; LB, lateral bending.

Sacral screw bending moments

Flexion, extension, and compression

Mean SS were the greatest during compression, and similar in magnitude during flexion and extension (Table 4, Fig. 4). During flexion and extension, SS with TLIF+2R and TLIF +4R were not significantly different from each other nor from NoLIF+2R (Fig. 4, p≥.11). In contrast, SS with both ALIF+2R and ALIF+4R were significantly less than with NoLIF+2R during flexion, extension, and compression

Table 4
Sacral screw bending moment

	Direction (Nm)			Lateral bending (Nm)		Axial rotation (Nm)	
Construct	Flexion	Extension	Compression	Ipsilateral	Contralateral	Ipsilateral	Contralateral
No LIF+2R (TLIF)	0.31±0.10	0.23±0.06	1.15±0.34	0.17±0.09	0.18±0.08	0.85±0.13	0.82±0.15
TLIF+2R	0.16±0.03	0.19±0.04	0.80±0.16	0.19±0.09	0.17±0.11	0.77±0.22	0.79±0.23
TLIF+4R	0.29±0.12	0.29±0.11	1.06±0.29	0.17±0.11	0.16±0.11	0.66±0.17	0.68±0.17
No LIF+2R (ALIF)	0.24±0.10	0.25±0.14	0.88±0.27	0.15±0.09	0.12±0.07	0.77±0.26	0.73±0.24
ALIF+2R	0.10±0.04	0.10±0.05	0.44±0.17	0.16±0.15	0.15±0.15	0.42±0.18	0.43±0.17
ALIF+4R	0.11±0.05	0.11±0.04	0.48±0.2	0.16±0.13	0.14±0.14	0.45±0.19	0.47±0.18

2R, 2-rod construction; 4R, 4-rod construction; ALIF, anterior lumbar interbody fusion; LIF, lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion.

Data are mean±SD.

Intact condition note shown.

(Fig. 4, p≤.02), but ALIF+4R was not different from ALIF+2R (Fig. 4, p≥.44). The SS was not statistically different with ALIF+2R versus TLIF+2R during flexion and extension (Fig. 4, p≥.08) although it was significantly less with ALIF+2R than TLIF+2R during compression (p=.04). Overall, the screw bending moments with ALIF+4R were significantly less than with TLIF+4R during flexion, extension, and compression (p≤.001).

Lateral bending

There were no significant intragroup or intergroup differences in SS on the ipsilateral or contralateral sides during LB (Fig. 4, p≥.42).

Axial rotation

During AR, ALIF+2R resulted in significantly less SS than NoLIF+2R and TLIF+2R on both the ipsilateral and contralateral sides (p<.001). The SS was significantly less with TLIF+2R versus NoLIF+2R on the ipsilateral side (p=.03) but not on the contralateral side (p=.47). Extra rods significantly reduced SS with TLIF (TLIF+4R vs. TLIF + 2R, p≤.01) but did not affect bending moments with ALIF (ALIF+4R vs. ALIF+2R, p≥.33). SS was significantly less with ALIF+2R versus TLIF+2R and TLIF+4R on both the ipsilateral and contralateral sides (Fig. 4, p≤.01).

Discussion

The lumbosacral junction is highly vulnerable to instrumentation failure in the setting of long segment fixation. A variety of techniques have been described to reduce stress concentration across high-risk sites including the use of anterior column support or use of supplemental posterior instrumentation across 3COs. No prior biomechanical studies have investigated the ability of multiple rods across the lumbosacral junction to reduce lumbosacral strain and mitigate the risk of instrumentation failure.

Our results confirm that with standard long segment posterior instrumentation (2 rods and iliac fixation), ALIF provides reduced rod strain and reduced SS at the lumbosacral junction compared with TLIF. This finding suggests that performing TLIF at the lumbosacral junction with a standard 2R technique does not sufficiently minimize rod strain and could predispose the construct to rod fracture. However, supplemental 4R fixation in TLIF constructs reduced lumbosacral rod strain nearly to levels achieved with ALIF in several directions of movement, thereby negating certain benefits of the ALIF in rod strain reduction. Notably, SS remained higher in TLIF constructs than in ALIF constructs despite supplemental fixation. Thus, the optimal strategy for improving overall construct stiffness and minimizing rod and screw strain is to place an ALIF at L5/S1 combined with standard 2R posterior fixation. Alternatively, for a posterior-only approach with TLIF at L5/S1, supplemental 4R fixation is biomechanically advantageous compared with other posterior constructs.

Anteriorly placed structural interbody support at the caudal end of a long deformity construct has long been recommended as the best method to minimize posterior rod strain and improve stability [24,25]. Multiple biomechanical studies of load sharing and anterior fixation have demonstrated the greater stability provided by the larger footprint the ALIF device compared with posterior techniques such as TLIF [4,26]. In a study of iliac fixation with S2 alar iliac screws, Sutterlin et al. [4] demonstrated the benefit of anterior fixation (with axial LIF) compared with TLIF in a lumbosacral construct, as well as the additive benefit of pelvic fixation with axial LIF. Kleck et al. [27] described a nearly 2-fold reduction in SS strain in an ALIF construct with screw fixation terminating in S1, but this benefit did not hold in the iliac condition. We found a significant benefit with ALIF despite the SS protective benefit of iliac screws in extension, compression, and AR. This difference could be accounted for by differences in study methods, including modes of loading and determining strain [27−29].Our results affirm the advantage of ALIF in longitudinal rod strain reduction and S1 screw protection associated with a long segment construct and iliac fixation. We attribute this benefit to the larger footprint of the ALIF device as well as the anterior integrated plate/screw fixation. However, a possible tradeoff of the anterior fixation is elevated rod strain relative to no interbody in AR (Fig. 3C); ultimately, no differences were observed in rod strain between interbody conditions, suggesting that this finding may be associated with choice of any lumbosacral interbody fusion.

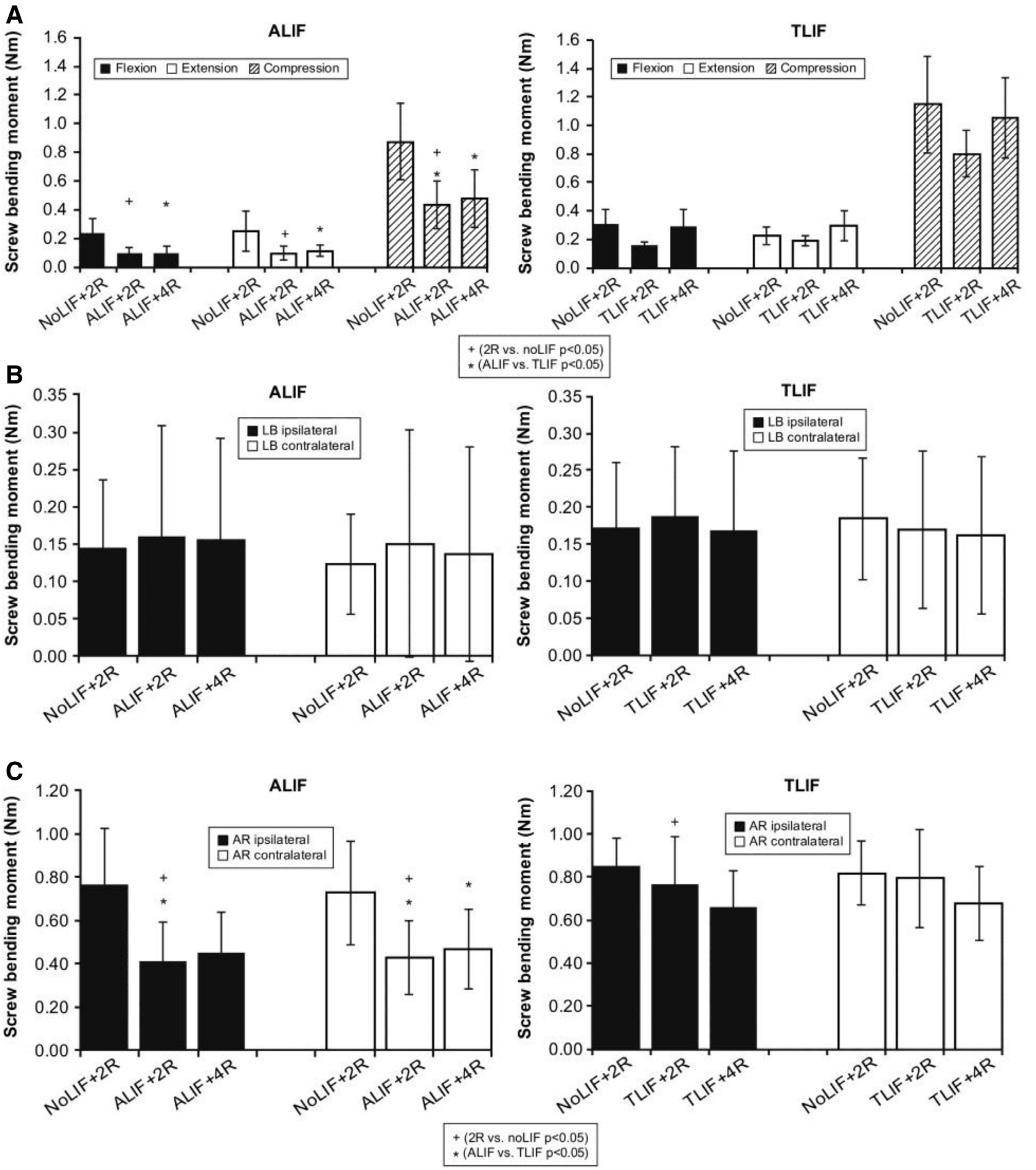

Fig. 4. Screw bending moments across ALIF and TLIF constructs. (A) Graphs demonstrate rod strain (microstrain, $\mu\varepsilon$) across flexion, extension, and compression; (B) left and right lateral bending; (C) left and right axial rotation. #p < .05 for 4R versus 2R. +p < .05 for ALIF or TLIF + 2R versus No LIF + 2R. *p < .05 for comparisons between ALIF and TLIF. Used with permission from (Institution blinded for review). ALIF, anterior lumbar interbody fusion; TLIF, transforaminal lumbar interbody fusion; 2R, 2-rod construction; 4R, 4-rod construction; AR, axial rotation; LB, lateral bending.

The 3COs such as pedicle subtraction osteotomy (PSO) are highly destabilizing procedures and are also associated with significant risk of rod fracture [12,30]. Multirod strategies have been shown to improve biomechanical stability and reduce posterior rod strain in the setting of this complex reconstructive technique [31]. Hallager et al. found reduced flexion and extension motion and reduced surface strain on the primary rod with 4R design across a 30° PSO model [32]. In an in vitro vertebrectomy model, Jager et al. reported 10-fold greater fatigue resistance (from 59,000 cycles to 561,214 cycles) with 4R than 2R constructs [33]. Recently, La Barbera et al. [19] demonstrated 50% reduction in primary rod strain in flexion using supplemental lateral rods for an L4 PSO construct; unlike our study, additional reductions were also seen in AR (42%) and LB (11%). However, this may be related to the greater destabilizing nature of the PSO or the use of rosette strain gauges that provide greater granularity and directionality of strain than traditional uniaxial strain gauges. The benefits of supplemental rods in PSO have also been mirrored by clinical studies demonstrating significantly reduced incidence of rod fracture with dual rod constructs [14,18].

Our rod strain measurements support the adaptation of such multirod strategies for the equally biomechanically demanding lumbosacral junction [1,6]. The observed benefit was most robust with the TLIF construct, which requires a destabilizing surgical maneuver involving a unilateral facetectomy. No benefit was observed in the SS in the TLIF group, potentially reflecting the choice of supplemental rod anchoring at the S1/ilium connection. Further studies evaluating choice of distal rod attachments for reducing the bending moment across the S1 screws may be needed.

Prior studies have demonstrated the benefit of supplemental rods across the lumbosacral junction, albeit not in iliac fixation and L5/S1 interbody spacer placement. A recent biomechanical study by Wang et al. [31] illustrated the stabilizing benefit of a 4R technique across the lumbosacral junction terminating with S1 screws. Although the study construct did not include anterior column fixation or iliac fixation in the 4R construct, the greatest benefit was observed in flexion, extension, and AR. Similarly, in our study, we noted the greatest benefits of supplemental rods in the TLIF group in flexion, extension, and compression. Given the similarities in rod orientation of the supplemental rods (side-by-side), this finding suggests that geometric orientation of the supplementary rods relative to the primary rod may determine the axis in which the primary benefit is observed. Parallel, or slightly angled supplemental rods could create a trapezoidal cross-sectional area, resulting in greater stiffness during sagittal plane bending (flexion and extension).

Notably, we found no additional benefit when combining ALIF with supplemental rods. This finding is perhaps caused by the larger footprint of the ALIF device and extra stabilizing effect of anterior fixation, which emphasizes the independent value of ALIF or supplemental posterior instrumentation but illustrates the lack of synergy between these strategies.

In an era of evidence-based medicine, it is essential to critically evaluate surgical strategies that maximize outcomes, reduce instrumentation failure, and provide construct longevity. The results of our study provide a framework for biomechanical optimization at the lumbosacral junction and serve as an impetus for further clinical investigation into the benefits of supplemental rod use for fracture prevention in deformity correction surgery. Although ALIF demonstrates clear benefit over posterior only approaches, surgeons must consider the clinical ramifications of a combined anterior/posterior approach, including increased operative time [34] and expanded surgical risk profile. Given the near biomechanical equipoise between ALIF and TLIF with supplemental rods, our results affirm the importance of either anterior column reconstruction or supplementation of posterior instrumentation, providing the surgeon with rough guidelines for optimal construct design.

Limitations

Several limitations to this study may constrain the broad applicability of our findings. First, the biomechanical test conditions are representative of the immediate postoperative condition only and cannot be readily extrapolated to account for changes that occur in vivo, and the degree to which biomechanical factors correlate to clinical results remains unknown. Additionally, to control for segmental lordosis between no LIF and ALIF or TLIF constructs, we did not release the posterior instrumentation during interbody cage placement. Although strain measurements were rezeroed after interbody cage placement, this technical limitation may not only impact preload strain and resultant observations but also limit distraction during disc space access for both interbody approaches. The restricted disc space access may differentially affect the posterior rather than the anterior approach; thus, judicious attention was required for appropriate cage sizing with apposition at each end plate.

Lastly, although these findings offer a strategy for focal reduction of strain and maximized stiffness at the lumbosacral junction, the question of the impact of increased stiffness on adjacent instrumented or uninstrumented levels remains. Although improved distal biomechanics at the lumbosacral junction could yield improved construct longevity, whether the increase in global stiffness reciprocally predisposes to higher rates of proximal junction failure and kyphosis remains to be seen. Future studies applying different strain gauges or imaging technology could facilitate a more comprehensive understanding of strain across the entire posterior construct.

Conclusion

Integration of multiple strategies can mitigate rod fracture risk in long segment instrumentation. Use of ALIF at L5/S1 and the addition of supplemental rods with TLIF significantly improved rod strain and biomechanical stability.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.1016/j.spinee.2019.01.005.

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