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Sequential correction of sagittal vertical alignment and lumbar lordosis in adult flatback deformity

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ABSTRACT

Background: Flatback deformity, or lumbar hypolordosis, can cause sagittal imbalance, causing back pain, fatigue, and functional limitation. Surgical correction through osteotomies and interbody fusion techniques can restore sagittal balance and relieve pain. This study investigated sagittal vertical alignment (SVA) and lumbar lordosis correction achieved through sequential procedures on human spine specimens.

Methods: Human T10-sacrum specimens were stratified into 2 groups: degenerative flatback specimens had smaller L1-S1 lordosis compared to the iatrogenic group (26.1°±15.0° vs. 47.8°±19.3°, p<.05). Specimens were mounted in the apparatus in simulated standing posture with a nominal sacral slope of 45 degrees and subjected to a 400N compressive follower preload. Sequential correction of degenerative lumbar flatback deformity involved: anterior lumbar interbody fusion (ALIF) at L5-S1, ALIF at L4-5, lateral lumbar interbody fusion (LLIF) at L2-3 and L3-4, and posterior column osteotomy (PCO) at L2-3 and L3-4. In iatrogenic specimens, flatback deformity was created by performing a posterior *in-situ* immobilization using pedicle screw instrumentation at L4-L5-S1 followed by distraction across the pedicle screws. We then performed LLIF at L2-3 and L3-4, followed by PCO at L2-3 and L3-4.

Results: Statistically significant incremental corrections were noted in SVAs and lordosis after L5-S1 ALIF, L4-5 ALIF, and PCO in degenerative flatback specimens. For the iatrogenic group, statistically significant worsening was noted in measures of standing alignment after L4-L5-S1 hypolordotic fusion. Subsequent LLIF at L2-3 and L3-4 did not significantly improve sagittal alignment. However, after PCO at L2-3 and L3-4, final alignment parameters were not significantly different than preoperative baseline values prior to hypolordotic fusion.

Conclusions: ALIF cages in the lower lumbar segments significantly improved sagittal alignment in degenerative flatback specimens. In the upper lumbar segments, LLIF cages alone were ineffective at enhancing lumbar lordosis. LLIF cages in conjunction with PCO improved alignment parameters in degenerative and iatrogenic flatback deformities.

Introduction

The first observation of flatback deformity was made in the 1970s, where sagittal malalignment of the spine was clinically identified in patients presenting with inclination of the trunk in the setting of lumbar hypolordosis [1,2]. Affected patients reported symptoms of muscular pain throughout the back and lower extremities, as well as an inability to remain upright without invoking compensatory mechanisms [1]. These

FDA device/drug status: Approved for this indication (Pedicle screws, Anterior Lumbar Interbody Fusion (ALIF) cages, Lateral Lumbar Interbody Fusion (LLIF) cages).

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mechanisms, including pelvic retroversion, hip and knee flexion, ankle extension, and thoracic hyperextension can result in increased energy expenditure. Over time patients will fatigue, causing further decompensation of their sagittal alignment and functional disability [3].

The importance of maintaining sagittal alignment has become increasingly recognized. Global spinal alignment is objectively assessed through determination of the sagittal vertical axis (SVA), a measurement of the distance between the C7 plumb line and a vertical line through the posterior superior corner of the S1 vertebra [4]. A value over 5 cm indicates sagittal imbalance. Studies evaluating the clinical implications of sagittal imbalance have associated it with increased disability and pain, lower patient satisfaction, and worse quality of life [4–12]. The relationship is linear- as positive sagittal imbalance increases, so does the severity of a patient's symptoms [11].

The etiology of flatback deformity can be iatrogenic or degenerative in nature. Iatrogenic flatback is a complication of posterior fusion surgery of the thoracolumbar spine. Historically, this occurred after use of distraction instrumentation extending into the lumbar spine [1,2,13,14]. Additional causes include a maligned fusion, pseudoarthrosis with deformity progression, thoracolumbar kyphosis, and decompensation of vertebral segments adjacent to the fusion mass [13]. Degenerative flatback is a deformity commonly seen in the Asian population [15]. It is attributed to progressive deterioration of the lumbar spine over time, resulting in hypertrophy of the facet joints, loss of disc height, and significant weakness of the back extensor musculature, all of which contribute to loss of lumbar lordosis [15–18].

Management of flatback deformity often necessitates operative intervention with the goal of restoring physiological lordosis and correcting sagittal malalignment. A number of different techniques have been developed to accomplish these objectives. The pedicle subtraction osteotomy (PSO) is a 3-column closing wedge osteotomy that can afford up to 35 degrees of lordosis correction, but is associated with a high degree of technical difficulty and elevated complication risk profile [13,19]. Conversely, posterior column (facet) osteotomy (PCO) is a less extensive technique that resects the posterior elements and shortens the posterior column, producing up to 10 degrees of lordosis per level performed [2,13]. When utilized in conjunction with lordotic intervertebral cages, such as those placed anteriorly or laterally in the ALIF (anterior lumbar interbody fusion) and LLIF (lateral lumbar interbody fusion) procedures respectively, the literature suggests that greater lordosis correction is achievable [20–24]. However, objective data on the amount of correction obtained is currently lacking. Our biomechanical study was designed to determine the degree of SVA and lumbar lordosis correction achieved through sequential procedures in multiple spine segments, including placement of lordotic cages and use of the PCO. We hypothesized that the combined use of these procedures would produce a significant improvement in both parameters (SVA and lordosis), restoring these values to the normal range.

Methods

Specimens

Fifteen (15) fresh-frozen human thoracolumbar (T10-sacrum) spine specimens were utilized for this study. The muscle tissue was dissected off the specimens, while preserving the intervertebral discs, all ligaments, and posterior bony structures.

Computed tomography (CT) based specimen-specific anatomic and kinematic models were built for each specimen to facilitate analysis of the experimental data. This technique allows for continuous, non-invasive measurement of 3-dimensional vertebral position and motion throughout the experimental testing protocol [25]. For kinematic model development, a minimum of 5 radiopaque spheres, serving as fiducial markers, were embedded in the vertebral bodies and sacrum. We obtained fine slice (0.3 mm) axial CT scans of the specimen after the embedding of the fiducial markers and prior to the experiments. Anatomic 3-D solid models were constructed of each vertebral body and sacrum from these axial CT scans (Mimics, Materialize, Leuven, Belgium). Key landmarks (mid-sagittal plane anterior, center, and posterior endplate points and vertebral body centers) were identified on each bone reconstruction and used in subsequent data analysis.

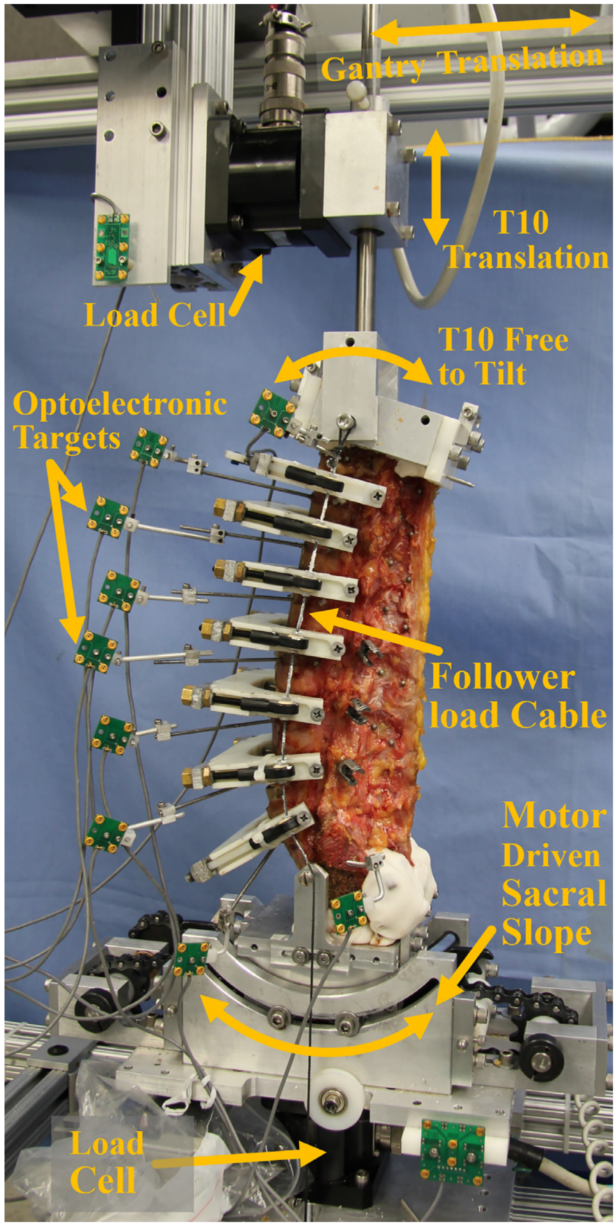

Fig. 1. T10-sacrum spine specimen undergoing testing.

Apparatus

The T10-sacrum specimen was mounted in the test apparatus in a posture that approximated a standing posture [26]. The apparatus (Fig. 1) allowed us to adjust the sacral slope by tilting the sacrum in the sagittal plane around the midpoint of its superior endplate. The cup holding the specimen's T10 vertebra was allowed to move in the caudal-cephalic direction to account for changing vertical height in response to changing sacral slope. The angular motion of the T10 vertebra in the sagittal plane (T10 tilt) was unconstrained. The anterior-posterior position of the T10 vertebra relative to the sacrum could be adjusted as needed to accommodate the standing posture. Multi-axis load cells (AMTI, Watertown, MA) were mounted at the base and top of the

Table 1
Mean (1 standard deviation) *starting* sagittal parameters for specimens of both cohorts (degenerative and iatrogenic).

Group	Sacral slope (degrees)	L4-S1 lordosis (degrees)	L1-S1 lordosis (degrees)	L1-S1 SVA (mm)	T10-S1 SVA (mm)
Degenerative: (n=7)	47.2 (7.5)	−23.0 (9)	−26.1 (15)	56.3 (15.2)	84.6 (26)
Iatrogenic: (n=6)	48.9 (12.4)	−35.1 (11.8)	−47.8 (19.3)	24.3 (16.6)	24.2 (26)
p-value	.8	.07	.05	.005	.002

Negative angle values indicate lordosis, and positive values kyphosis.
Positive SVA values indicate anterior offset relative to the sacrum.
p-values were calculated using 2-tailed student's t-tests on 2 independent samples assuming unequal variances (heteroscedastic samples). $p<.05$ was considered statistically significant because there was only 1 comparison per alignment parameter.

specimen to measure forces and moments applied to the specimen at the bottom and top boundaries, respectively.

Due to muscle tone, muscle activity, and weight-bearing, the human spine is always under some level of compressive preload *in vivo*. The apparatus allowed application of compressive follower preload representing the physiologic preload acting in the lumbar spine [27]. The 400N compressive preload was applied using bilateral loading cables that were attached to the cup holding the T10 vertebra (Fig. 1). The cables passed freely through guides anchored to each vertebra and were connected to a loading system under the specimen.

To assess vertebral position and motions, infrared targets were rigidly attached to each vertebral body. These targets were tracked using an optoelectronic motion measurement system (Optotrak® Certus, Northern Digital, Waterloo, Ontario, Canada). A reference or stationary target that defines the specimen's anatomic coordinate system was mounted at the base of the apparatus.

Specimens were wrapped in saline soaked towels to prevent dehydration of the tissues, and all testing was completed in a single testing session.

Experimental protocol

Specimens 1 and 2 were used as trial specimens to finalize the protocol steps and testing parameters. These 2 specimens were not included in the final data analysis.

The remaining 13 specimens were stratified into the iatrogenic or degenerative flatback deformity group based on the initial amount of disc collapse at L5-S1 and/or L4-5 and lordosis across L1-S1 and L4-S1 (Table 1). Seven (7) specimens were assigned to the degenerative flatback deformity group (Age 57.9±7.3 years; 5M, 2F) with an average lordosis across L4-S1 of 23.0±9.0 degrees and L1-S1 lordosis of 26.1±15.2 degrees.

The remaining 6 specimens were assigned to the iatrogenic group (Age 55.2±7.5 years; 5M, 1F). The baseline lordosis parameters in these 6 specimens had L4-S1 lordosis of 35.1±11.8 degrees and L1-S1 lordosis of 47.8±19.3 degrees; these lordosis values compare well with the normative values in the adult population.

Iatrogenic lumbar flatbacks were created by sequentially performing posterior *in situ* fusion using pedicle screw instrumentation at L4-L5-S1 and then creating a hypolordotic fusion at L4-L5-S1 by using distraction across pedicle screws at each level. The baseline alignment parameters of the specimens in the iatrogenic group before creating a hypolordotic L4-L5-S1 fusion were used as the basis to compare the alignment before and after the sequential corrective procedure.

Degenerative lumbar flatback

Correction of degenerative flatback deformity was performed by using ALIF cages at the L5-S1 and L4-5 disc spaces and using lateral cages with subsequent PCO at the proximal L3-4 and L2-3 segments. Specimens in the degenerative flatback cohort were tested in the following sequence: (1) Intact (Note: to improve testing flow, L4-S1 pedicle screws were placed prior to intact specimen testing), (2) L5-S1 fusion using a stand-alone ALIF cage (Synfix® Evolution Secured Spacer System, DePuy Synthes, Raynham MA), (3) stand-alone ALIF cage at L4-5, (4) LLIF cages at L2-3 and L3-4 (Cougar LS® Lateral Cage System, DePuy Synthes, Raynham MA), and (5) PCO at L2-3 and L3-4 (Fig. 2).

The LLIF cages implanted at L2-L3 and L3-L4 were 15-degree lordosis cages except as indicated in Table 2 where straight cages were used as deemed appropriate by the implanting surgeon considering the narrow disc heights. The cages were stabilized posteriorly using L2-L4 pedicle screws and rods. Compression between screws was applied before tightening the construct. PCO involved bilateral resection of the inferior articular processes of the cephalad vertebra of a spinal segment and resection of part of lamina, spinous process, and any bony and soft tissues that may obstruct posterior compression applied via pedicle screws. Curved rods were used posteriorly to accommodate improved lordosis across L2-4 PCO.

Iatrogenic lumbar flatback

For iatrogenic flatback deformity across L4-S1, lordosis correction was performed above the L4-S1 fusion using lateral cages and PCO in the proximal segments. Specimens in the iatrogenic lumbar flatback cohort were tested in the following sequence: (1) Intact, (2) posterior in-situ fusion at L4-L5-S1 without significantly altering the lordosis across L4-L5-S1, (3) hypolordotic fusion at L4-S1 created by distraction across pedicle screws at each level (L4-5 and L5-S1), (4) LLIF cages at L2-3 and L3-4, and (5) PCO at L2-3 and L3-4 (Fig. 3). The implant sizing of L2-4 LLIF cages can be found in Table 3.

Sagittal alignment parameters were recorded at the conclusion of each procedure using specimen-specific analysis of the neutral posture of the thoracolumbar specimens under 400N compressive preload. These parameters included degree of lordosis between segments of the lumbar spine and anterior offsets of the center of the L1 and T10 vertebral bodies relative to the center of S1 superior endplate (modified definition of L1-S1 and T10-S1 SVA).

Statistical analysis

Within-group analyses were performed separately on the data from degenerative and iatrogenic specimen groups. Pairwise comparisons were performed between: (1) 2 consecutive steps, and (2) between the initial and final values. Two-tailed, *paired* Student's t-tests were performed to assess the statistical significance of changes in L1-S1 SVA, T10-S1 SVA, and L1-S1 lumbar lordosis with each successive procedure and from initial value to final value. The Bonferroni correction was applied to account for statistical errors in the setting of multiple comparisons (n=5). Consequently, $p<.01$ was considered statistically significant (adjusted alpha=.05/5=.01) [28].

Between-groups analyses were performed to: (1) assess the differences in starting parameters of specimens in the 2 groups as set up in the apparatus; and (2) compare alignment parameters (L1-S1 lordosis, SVAs) of flatback deformities caused by degenerative versus iatrogenic causes of hypolordosis across L4-S1. Each alignment parameter from the 2 independent groups was compared using 2-tailed Student's t-test.

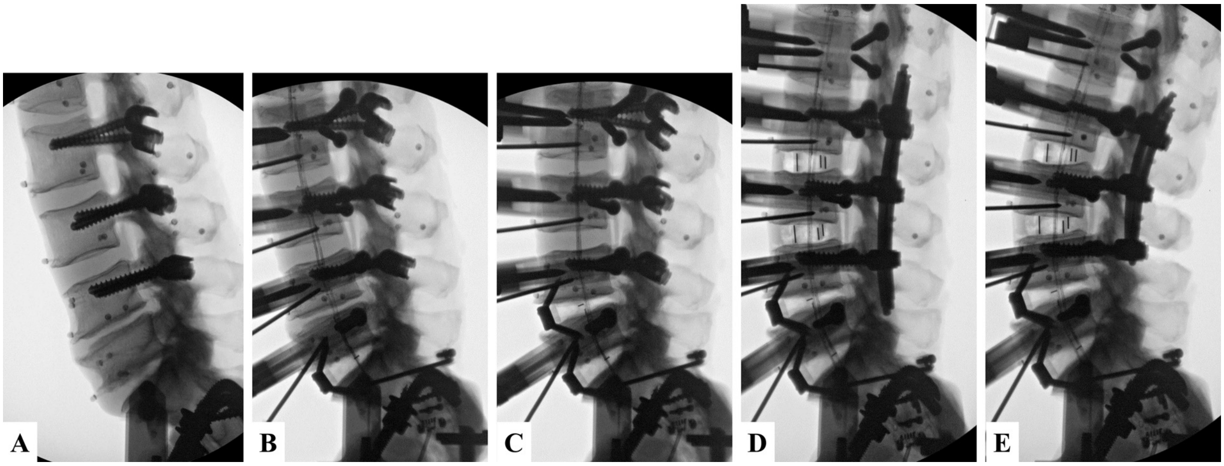

Fig. 2. Radiographic imaging of stepwise procedures performed on a degenerative flatback specimen (Specimen 9), (A) intact specimen, (B) after insertion of L5-S1 ALIF cage, (C) after insertion of L4-L5 ALIF cage, (D) after insertion of L2-3 and L3-4 LLIF cages with posterior stabilization, and (E) after PCO at L2-3 and L3-4 and using curved rods to accommodate improved lordosis across L2-4.

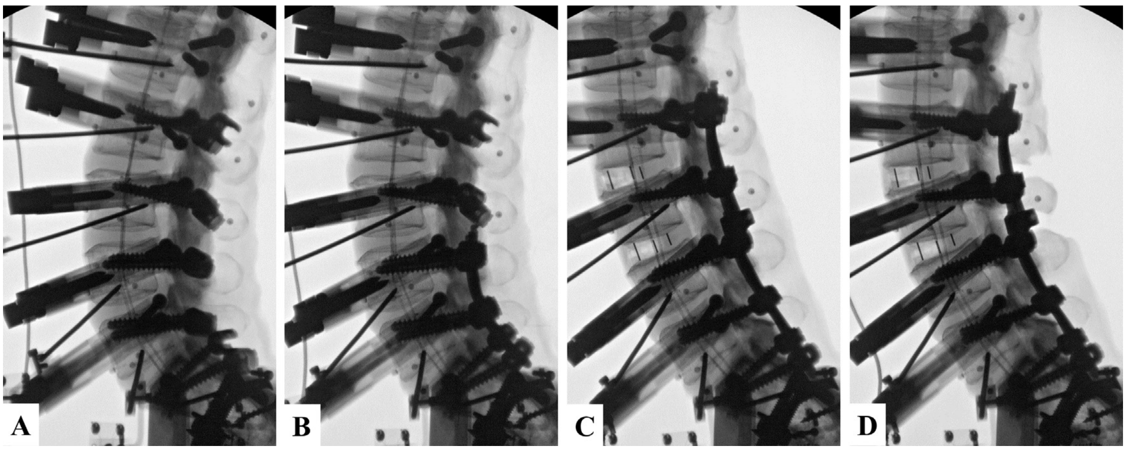

Fig. 3. Radiographic imaging of stepwise procedures performed on iatrogenic specimen (Specimen 10), (A) intact under 400N preload, (B) after in-situ fusion between L4-S1, (C) following distraction of the construct and creation of a hypolordotic fusion at L4-S1 and placement of LLIF cage at L2-3 and L3-4 with posterior stabilization, and (D) after PCO at L2-3 and L3-4 with posterior stabilization using curved rods to accommodate improved lordosis across L2-L4.

Table 2
Cage sizes placed in *degenerative* specimens.

Specimen number	L5-S1 ALIF cage	L4-5 ALIF cage	L2-3 LLIF cage	L3-4 LLIF cage
6	13.5 mm x 14°	10.5 mm x 6°	55 × 10 × 18 mm (straight)	55 × 10 × 18 (straight)
8	13.5 mm x 14° SD	13.5 mm x 18° M	50 × 8 × 18 mm (straight)	50 × 10 × 18 (straight)
9	13.5 mm x 18° SD	13.5 mm x 18° S	50 × 12 × 18 mm (15°)	50 × 12 × 18 mm (15°)
11	13.5 mm x 18° S	13.5 mm x 18° SD	50 × 12 × 18 mm (15°)	50 × 12 × 18 mm (15°)
12	13.5 mm x 18° SD	15.0 mm x 18° MD	55 × 12 × 18 mm (15°)	55 × 12 × 18 mm (15°)
13	13.5 mm x 18° SD	13.5 mm x 18° S	50 × 12 × 18 mm (15°)	50 × 8 × 18 mm (straight)
14	13.5 mm x 18° S	15.0 mm x 18° MD	55 × 12 × 18 mm (15°)	55 × 12 × 18 mm (15°)

S, SD, M, MD refer to the footprint size, dimensions are as follows: S 32 × 25 mm, SD 32 × 28 mm, M 36 × 28 mm, MD 36 × 31 mm.

Table 3
Cage sizes placed in iatrogenic specimens.

Specimen number	L2-3 LLIF cage	L3-4 LLIF cage
3	18 × 12 × 55 (15°)	18 × 12 × 55 (15°)
4	18 × 12 × 55 (15°)	18 × 12 × 55 (15°)
5	18 × 10 × 45 (straight)	18 × 10 × 50 (straight)
7	18 × 12 × 50 (15°)	18 × 10 × 50 (straight)
10	18 × 12 × 50 (15°)	18 × 12 × 50 (15°)
15	18 × 12 × 50 (15°)	18 × 12 × 50 (15°)

Level of significance for between-group comparisons was set at p<.05 because only 1 comparison per alignment parameter was performed.

Results

Degenerative flatback deformity correction

The specimens in the degenerative deformity group had significantly larger preoperative values of T10-S1 SVA and L1-S1 SVA when compared to the specimens in the iatrogenic group despite having similar sacral slope values. This was primarily due to the smaller values of L4-S1 and L1-S1 lordosis of the degenerative specimens (Table 1).

In this cohort, statistically significant incremental corrections (relative to the prior step) were noted in SVAs and L1-S1 lordosis after the L5-S1 ALIF, L4-5 ALIF, and PCO procedures (p<.01) (Fig. 4). The L5-S1

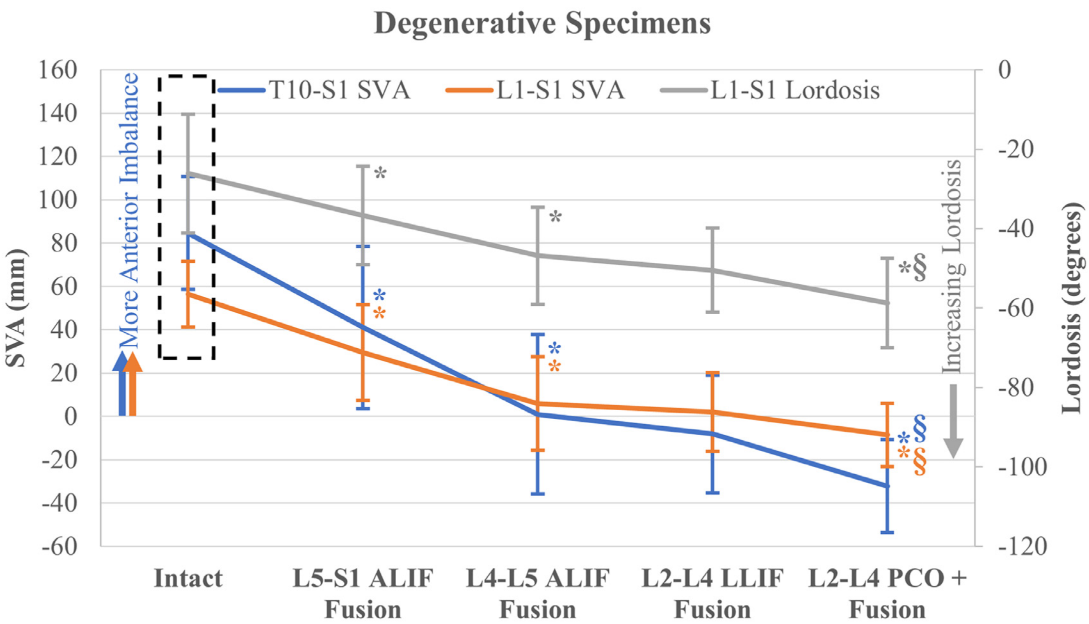

Figure 4. Average T10-S1 SVA, L1-S1 SVA, and L1-S1 Lordosis values obtained with sequential procedures in degenerative flatback specimens. Dashed box denotes parameters of degenerative flatback deformity.
* Significant difference from previous protocol step (p<.01). § Significant difference between preoperative and post L2-L4 PCO conditions (p<.01).

Table 4
Average (standard deviation) correction obtained by sequential surgical procedures in degenerative flatback specimens.

Procedure	T10-S1 SVA (mm)	p-value	L1-S1 SVA (mm)	p-value	L1-S1 lordosis (degrees)	p-value
L5-S1 ALIF	−43.6 (19.4) range: 15.4 to 74.1	.001	−26.9 (11.7) range: 9.4 to 44.5	.0009	−10.5 (3.9) range: −16.1 to -5.0	.0004
L4-5 ALIF	−40.1 (10.3) range: 24.6 to 52.2	<.0001	−23.5 (6.1) range: 14.3 to 31.6	<.0001	−10.2 (2.9) range: −13.0 to −6.6	<.0001
LLIF L2-3, L3-4	−9.1 (15.7) range: −22.3 to 25.9	.2	−3.8 (7.5) range: -10.5 to 12.5	.2	−3.6 (5.3) range: −9.8 to 6.6	.12
PCO L2-3, L3-4	−24.0 (8.2) range: 12.7 to 35.0	.0002	−10.6 (4.1) range: 4.7 to 15.0	.0005	−8.3 (2.3) range: −12.1 to −5.1	<.0001

Negative values indicate reduction of SVA and increase in lordosis.
p-values indicate significance when compared to the *preoperative* sagittal malalignment.
p-values <.01 are significant.

Table 5
Degenerative cohort posture measures: preoperative and after deformity correction with PCO (last protocol step).

	Preoperative	Postoperative	Correction	p-Value
T10-S1 SVA	84.6 (26) mm	−32.1 (21.5) mm	−116.7 (17.8) mm	<.0001
L1-S1 SVA	56.3 (15.2) mm	−8.6 (14.6) mm	−64.9 (9.2) mm	<.0001
L1-S1 Lordosis	−26.1 (15) deg	−58.7 (11.3) deg	−32.6 (10.5) deg	.0002

The postural correction and significance are shown.
p-values are calculated using 2-tailed, paired student's t-tests (Significance level p<.01).

lordosis improved by an average of −9.6±5.8 degrees with L5-S1 ALIF, while L4-5 lordosis improved by −10.1±4.7 degrees with L4-5 ALIF. L2-3 lordosis improved by −1.9±2.4 degrees and L3-4 lordosis by −0.8±1.9 degrees with L2-4 LLIF. No significant change in SVA or lordosis was seen after LLIF alone (Table 4). A statistically significant overall correction was noted when comparing preoperative (intact) values to those after completion of the PCO (Table 5).

Iatrogenic flatback deformity correction

For the specimens in the iatrogenic group (n=6), as intended, the L4-S1 *in situ* fusion caused a minimal change in L4-S1 and L1-S1 lordosis: −0.9±4.9 degrees (p=.7) and −1.2±5.0 degrees (p=.6), respectively. In contrast, iatrogenic deformity generated by distraction applied across the pedicle screws at L4-5 and L5-S1 caused a loss of L4-S1 lordosis that averaged 12.7±4.0 degrees (−36.0±9.2 vs. −23.2±9.4, p=.0005). A statistically significant worsening was noted in all alignment parameters (T10-S1 SVA, L1-S1 SVA, and L1-S1 Lordosis) after hypolordotic fusion across L4-S1 (Fig. 5). The severity of the flatback deformity caused by iatrogenic L4-S1 hypolordotic fusion was comparable to the native deformity of the degenerative specimen cohort (p>.2). (Table 6).

Subsequent LLIF at L2-3 and L3-4 did not show significant improvement in sagittal alignment. Average corrections obtained by sequential surgical procedures (LLIF and LLIF+PCO) in the iatrogenic flatback specimens are shown in Table 7. The increase in L1-S1 lordosis after performing the PCO, while adding 5.8 degrees of lordosis across L1-S1 compared to LLIF alone, was not significant (p=.07). The improvements in the T10-

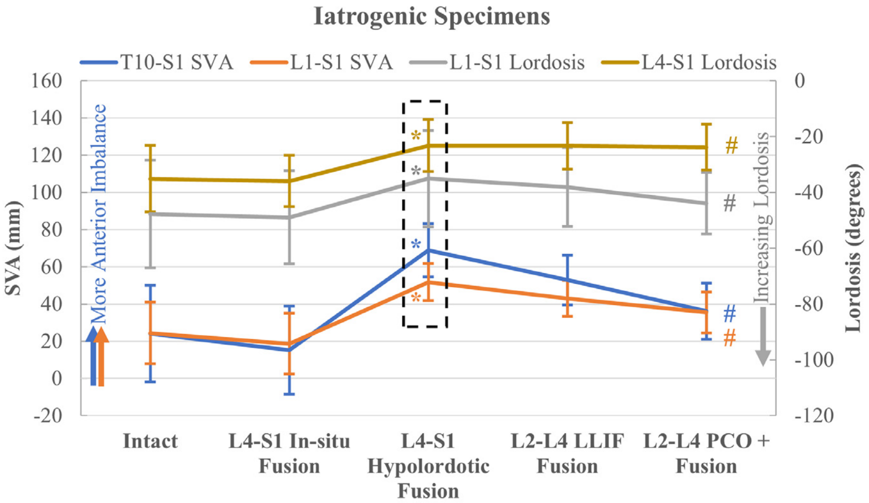

Fig. 5. Average T10-S1 SVA, L1-S1 SVA, and L1-S1 Lordosis values obtained with sequential procedures in specimens in the iatrogenic group. Dashed box denotes parameters of iatrogenic flatback deformity. * Significant difference from previous surgical step. # Not different than the intact condition (Posture returned to the preoperative state).

Table 6
A comparison of severity of flatback deformities.

Specimens	Sacral slope (degrees)	L4-S1 lordosis (degrees)	L1-S1 lordosis (degrees)	L1-S1 SVA (mm)	T10-S1 SVA (mm)
Degenerative Flatback (Protocol step 1) (n = 7)	47.2 (7.5)	-23.0 (9.0)	-26.1 (15)	56.3 (15.2)	84.6 (26)
Iatrogenic Flatback (Protocol step 3) (n = 6)	47.9 (12.0)	-23.2 (9.4)	-35.1 (17.3)	51.8 (10.0)	68.9 (14.3)
p-value	.9	1.0	.4	.5	.2

Degenerative deformity data is from before any surgery was performed on specimens in that cohort, while iatrogenic deformity data is from protocol step 3 - L4-S1 hypolordotic fusion.
Negative angle values indicate lordosis, and positive values kyphosis.
Positive SVA values indicate anterior offset relative to the sacrum.
p-values were calculated using 2-tailed student's t-tests assuming 2 independent samples with unequal variances (heteroscedastic samples). p<.05 was considered statistically significant because there is only 1 comparison per alignment parameter.

Table 7
Average correction obtained by sequential surgical procedures in the iatrogenic flatback specimens.

Protocol Step	Change in T10-S1 SVA, mm (standard deviation)	p-value	Change in L1-S1 SVA, mm (standard deviation)	p-value	Change in L1-S1 lordosis, degrees (standard deviation)	p-value
LLIF L2-3, L3-4	−16.0 (13.3), range: −2.4 to −33.0	.03	−8.8 (7.9), range: −1.5 to −20.0	.04	−3.0 (5.6), range: −11.5 to 4.3	.2
PCO L2-3, L3-4	−16.7 (12.4), range: −3.9 to −38.2	.01	−7.5 (5.1), range: −2.0 to −15.4	.009	−5.8 (5.3), range: −15.4 to −1.3	.07

Negative values indicate reduction of SVA and increase in lordosis.
p-values indicate significance when compared to the previous protocol step. p- values <.01 are significant.

Table 8
Iatrogenic cohort posture measures: preoperative and after correction of flatback deformity using L2-4 LLIF and PCO.

	Intact baseline (before hypolordotic fusion)	Post LLIF+PCO	Difference	p-Value
T10-S1 SVA	24.2 (26) mm	36.1 (15.1) mm	12 (30.5) mm	.4
L1-S1 SVA	24.3 (16.6) mm	35.5 (11) mm	11.2 (17.7) mm	.2
L1-S1 Lordosis	−47.8 (19.3) deg	−43.9 (11.1) deg	3.9 (10.9) deg	.4

The postural differences and significance are shown.
p-values are calculated using 2-tailed, paired student's t-tests (Significance level p<.01).

S1 SVA and L1-S1 SVA caused by the PCO, however, were statistically significant (p=.01 and p=.009, respectively).

With the addition of PCO at L2-3 and L3-4, the final alignment parameters were not significantly different than their preoperative baseline values prior to creating (iatrogenic) hypolordotic fusion (Table 8): mean difference of 12 mm for T10-S1 SVA (p=.4), 11 mm for L1-S1 SVA (p=.2), and 4 degrees of L1-S1 lordosis (p=.4).

Correction of lordosis at upper lumbar segments

The addition of the LLIF cages alone changed L2-4 lordosis by an average of 2-3 degrees which was not sufficient to significantly improve L2-4 lordosis in the degenerative or iatrogenic specimens (Table 9). However, compared to LLIF alone, the addition of PCO to LLIF cages significantly increased L2-4 lordosis by approximately 8 degrees in the de-

Table 9
Lordosis across L2-4 after sequential procedures.

	Average initial L2-4 Lordosis (degrees)	Average L2-4 lordosis after LLIF cage placement (degrees)	p-value	Average L2-4 lordosis after PCO (degrees)	p-value
Degenerative specimens	−2.5 (9.1) range: −11.9 to 12.2	−5.3 (7.7) range: −15.2 to 8.3	.03	−14.0 (8.6) range: −22.6 to 1.3	.0006
Iatrogenic specimens	−13.7 (3.9) range: −17.9 to -7.2	−15.7 (2.2) range: −17.3 to −12.7	.2	−20.9 (5.4) range: −30.7 to −15.1	.05

Negative values indicate lordosis, positive values represent kyphosis.
p-values compare lordosis after LLIF cage placement to initial lordosis and compare lordosis after PCO to lordosis after LLIF cage placement.
p-values <.01 are significant.

generative specimens (p<.01) and improved lordosis by approximately 5 degrees in the iatrogenic specimens, but without reaching statistical significance (p=.05).

Discussion

Our study was performed to objectively assess the correction in SVA and lumbar lordosis achieved through different procedures performed sequentially in spine specimens. The specimens that were included in the degenerative group were noted to have a positive average initial L1-S1 SVA of 56 mm and T10-S1 SVA 85 mm (Table 6), indicative of sagittal imbalance at baseline secondary to loss of lordosis caused by disc degeneration and height loss across L4-S1. By performing the anterior lumbar interbody fusions in the lower lumbar segments and PCO in the upper lumbar segments we were able to obtain a statistically significant correction in both SVA and lumbar lordosis. This indicates that these techniques may be effective approaches when addressing patients presenting with degenerative flatback deformity.

At 52 mm of L1-S1 SVA and 69 mm of T10-S1 SVA (Table 6), these starting average SVA values for the specimens in the iatrogenic group were closer to neutral, suggesting a relatively balanced sagittal alignment prior to intervention. Iatrogenic sagittal malalignment was induced by posterior distraction across an in-situ L4-S1 fusion. The parameters of the malalignment induced by distraction were statistically not different from the malalignment caused by hypolordosis secondary to degenerative changes at L4-5 and L5-S1 in the degenerative cohort (p>.2, Table 6). The goal of the subsequent procedures in the iatrogenic group was to try to correct SVA and total L1-S1 lumbar lordosis back to their baseline values. This was largely achieved, as we found that there was no statistically significant difference between the initial and final parameter values for this group of specimens (p>.2, Table 8).

Considering the clinical reports of utilizing interbody fusion cages and posterior column osteotomy to address sagittal malalignment [2,13,21–24] we sought to determine the amount of SVA, and lumbar lordosis correction obtained with each of these procedures. Our findings indicate that ALIF at the lowest 2 lumbar levels were the most powerful technique employed while LLIF using primarily static 15-degree cages at upper lumbar levels was the least impactful. ALIF provided correction of sagittal alignment parameters of approximately 40-43 mm in T10-S1 SVA, 23-27 mm improvement of L1-S1 SVA, and a gain of over 10 degrees of lordosis at each level with placement of these cages. In comparison, the change in sagittal alignment after L2-L4 LLIF at was 16mm in T10-S1 SVA, 9mm in L1-S1 SVA, and less than 3 degrees of L2-L4 lordosis.

The discrepancy in correction magnitude of lordosis between the ALIF and LLIF levels can likely be attributed to the presence or removal of the anterior longitudinal ligament (ALL). The surgical technique for placement of the ALIF cages necessitates sectioning of the ALL, which allows for greater anterior height increase and therefore greater lordosis correction. LLIF cages used in this study ranged from straight to a maximum of 15° of lordosis. The 15° wedge angle of the cage is expected to provide lordotic correction. However, with the ALL intact the average segmental correction of all levels implanted with a 15° LLIF from both cohorts was −1.9 degrees after LIIF cage placement and -4.1 degrees after PCO. These findings suggest that cage angle alone does not dictate magnitude of lordotic correction in the upper lumbar spine using LLIF.

Clinical studies have examined the role of the interbody techniques in correcting sagittal imbalance. Lee et al. evaluated sagittal alignment after performing an oblique lateral interbody fusion (OLIF) and PCO compared to PSO [23]. No statistically significant differences in postoperative SVA or lumbar lordosis were noted, but PSO was found to have significantly higher rate of pseudoarthrosis and blood loss. These findings prompted the authors to conclude that multilevel OLIF and PCO was an effective alternative to PSO for these patients. Similarly, Strom et al. retrospectively compared PCO with and without the addition of LLIF in a group of 92 patients [19]. Corrections in lumbar lordosis were significantly higher for those undergoing LLIF and PCO compared to those who only underwent osteotomy. Additionally, fewer complications, greater pain relief, and faster recovery were noted in the LLIF and PCO group. Finally, Janjua et al. reviewed 50 patients diagnosed with flatback deformity who underwent ALIF with hyperlordotic cages [24]. Correction was supplemented with posterior osteotomies (including PSO and Smith-Petersen osteotomy) to avoid impingement of the nerve roots. A statistically significant difference in SVA and lumbar lordosis was noted compared to preoperative values, leading the authors to propose that hyperlordotic ALIF are efficacious and should be given consideration, particularly in light of the complications associated with PSO. While these studies have sought to assess the clinical utility of these techniques and alternatives to the highly morbid PSO procedure, quantitative data from a cadaveric study was lacking in the literature. This provided an opportunity for our study to complement and add to the current body of knowledge on sagittal alignment correction in flatback deformity using interbody cages with and without PCO.

Limitations of this study include those inherent to the use of cadaveric specimens. The T10-sacrum specimen was mounted in the test apparatus in a posture that approximated the lumbosacral alignment during standing [26]. The sacral slope was adjusted around a nominal value of 45 degrees for specimens in both degenerative and iatrogenic groups (Table 1). The sacral slope remained unchanged throughout the experiment. The apparatus allowed application of a 400N compressive follower preload representing the physiologic preload acting in the lumbar spine during standing [27] (Fig. 1). While cadavers provide quantitative data on sagittal correction, they do not account for the soft tissue structures that contribute to the final clinical outcome for a patient. When examining the data, a substantial standard deviation was noted in many of the values measured. This is likely attributable to the preoperative characteristics of the individual specimens; each level has inherently different baseline alignment and lordosis, and therefore these techniques may produce variability in results among specimens. However, similar trends were noted when examining the data obtained with each subsequent procedure in each specimen. While these factors may have impacted the statistical analysis, they likely also better model the clinical setting where patients can present with vastly different sagittal alignment parameters, and therefore improve the generalizability of our findings. Finally, a confluence of factors beyond our control including costs and availability of specimens, and time constraints on instrumentation loan for this project limited our sample size.

Conclusions

ALIF cages in the lower lumbar segments significantly improved sagittal alignment in adult degenerative flatback deformity. LLIF cages in the upper lumbar segments by themselves were not effective in correcting SVA or enhancing lumbar lordosis. LLIF cages in conjunction with PCO improved both lordosis and SVA alignment parameters in both degenerative and iatrogenic flatback deformities.

Declaration of competing interests

One or more of the authors declare financial or professional relationships on ICMJE-NASSJ disclosure forms.

Clinical relevance

Our biomechanical study determined the degree of correction of sagittal alignment achieved through sequential procedures in *multiple* spine segments, including placement of lordotic cages and use of the PCO. The combined use of these procedures produced a significant improvement in both lumbar lordosis and SVA parameters, restoring their values to the normal range in treating degenerative and iatrogenic deformities in the thoracolumbar spine.

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References

[1] Lu DC, Chou D. Flatback syndrome. Neurosurg Clin N Am 2007;18(2):289–94.
[2] Boody BS, Rosenthal BD, Jenkins TJ, Patel AA, Savage JW, Hsu WK. Iatrogenic flatback and flatback syndrome: evaluation, management, and prevention. Clin Spine Surg 2017;30(4):142–9.
[3] Bae J, Theologis AA, Jang J-S, Lee S-H, Deviren V. Impact of fatigue on maintenance of upright posture: dynamic assessment of sagittal spinal deformity parameters after walking 10 minutes. Spine (Phila Pa 1976) 2017;42(10):733–9.
[4] Klineberg E, Schwab F, Smith JS, Gupta MC, Lafage V, Bess S. Sagittal spinal pelvic alignment. Neurosurg Clin N Am 2013;24(12):157–62.
[5] Emami A, Deviren V, Berven S, Smith JA, Hu SS, Bradford DS. Outcome and complications of long fusions to the sacrum in the adult spine deformity: luque-galveston, combined iliac and sacral screw, and sacral fixation. Spine (Phila Pa 1976) 2002;27(7):776–86.
[6] Blondel B, Schwab F, Ungar B, et al. Impact of magnitude and percentage of global sagittal plane correction on health-related quality of life at 2 years follow up. Neurosurgery 2012;71(2):341–8.
[7] Booth KC, Bridwell KH, Lenke LG, Baldus CR, Blanke KM. Complications and predictive factors for the successful treatment of flatback deformity (fixed sagittal imbalance). Spine (Phila Pa 1976) 1999;24(16):1712–20.
[8] Mac-Thiong J-M, Transfeldt EE, Mehbod AA, et al. Can C7 plumbline and gravity line predict health related quality of life in adult scoliosis? Spine (Phila Pa 1976) 2009;34(15):E519–27.
[9] Smith JS, Singh M, Klineberg E, et al. Surgical treatment of pathological loss of lumbar lordosis (flatback) in patients with normal sagittal vertical axis achieves similar clinical improvement as surgical treatment in elevated sagittal vertical axis: clinical article. J Neurosurg Spine 2014;21(2):160–70.
[10] Bess S, Line B, Fu K-M, et al. The health impact of symptomatic adult spinal deformity: comparison of deformity types to United States population norms and chronic diseases. Spine (Phila Pa 1976) 2016;41(3):224–33.
[11] Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F. The impact of positive sagittal balance in adult spinal deformity. Spine (Phila Pa 1976) 2005;30(18):2024–9.
[12] Glassman SD, Berven S, Bridwell K, Horton W, Dimar JR. Correlation of radiographic parameters and clinical symptoms in adult scoliosis. Spine (Phila Pa 1976) 2005;30(6):682–8.
[13] Potter BK, Lenke LG, Kuklo TR. Prevent and management of iatrogenic flatback deformity. J Bone Joint Surg Am 2004;86(8):1793–808.
[14] Wiggins GC, Ondra SL, Shaffrey CI. Management of iatrogenic flat-back syndrome. Neurosurg Focus 2003;15(3):E8.
[15] Choi J-H, Jang J-S, Kim H-S, Jang I-T. What is the more appropriate proximal fusion level for adult lumbar degenerative flat back? World Neurosurg 2017;106:827–35.
[16] Lee JC, Cha J-G, Kim Y, Kim Y-I, Shin B-J. Quantitative analysis of back muscle degeneration in the patients with the degenerative lumbar flat back using a digital image analysis: comparison with the normal controls. Spine (Phila Pa 1976) 2008;33(3):318–25.
[17] Jang J-S, Lee S-H, Min J, Maeng DH. Changes in sagittal alignment after restoration of lower lumbar lordosis in patients with degenerative flat back syndrome. J Neurosurg Spine 2007;7(4):387–92.
[18] Le Huec JC, Charosky S, Barrey C, Rigal J, Aunoble S. Sagittal imbalance cascade for simple degenerative spine and consequences: algorithm of decision for appropriate treatment. Eur Spine J 2011;20(Suppl 5):699–703 Suppl 5.
[19] Strom RG, Bae J, Mizutani J, Valone F, Ames CP, Deviren V. Lateral interbody fusion combined with open posterior surgery for adult spinal deformity. J Neurosurg Spine 2016;25(6):697–705.
[20] Qandah NA, Klocke NF, Synkowski JJ, et al. Additional sagittal correction can be obtained when using an expandable titanium interbody device in lumbar Smith-Peterson osteotomies: a biomechanical study. Spine J 2015;15(3):506–13.
[21] Chan AK, Mummaneni PV, Shaffrey CI. Approach selection: multiple anterior lumbar interbody fusion to recreate lumbar lordosis versus pedicle subtraction osteotomy: when, why, how? Neurosurg Clin N Am 2018;29(3):341–54.
[22] Suh L-R, Jo D-J, Kim S-M, Lim Y-J. A surgical option for multilevel anterior lumbar interbody fusion with ponte osteotomy to achieve optimal lumbar lordosis and sagittal balance. J Korean Neurosurg Soc 2012;52(4):365–71.
[23] Lee KY, Lee J-H, Kang K-C, et al. Minimally invasive multilevel lateral lumbar interbody fusion with posterior column osteotomy compared with pedicle subtraction osteotomy for adult spinal deformity. Spine J 2020;20(6):925–33.
[24] Janjua MB, Ozturk AK, Ackshota N, et al. Surgical treatment of flat back syndrome with anterior hyperlordotic cages. Oper Neurosurg (Hagerstown) 2020;18(3):261–70.
[25] Havey RM, Goodsitt J, Khayatzadeh S, et al. Three-dimensional computed tomography based specimen-specific kinematic model for ex vivo assessment of lumbar neuroforaminal space. Spine (Phila Pa 1976) 2015;40(14):E814–22.
[26] Patwardhan AG, Sielatycki JA, Havey RM, et al. Loading of the lumbar spine during transition from standing to sitting: effect of fusion versus motion preservation at L4–L5 and L5–S1. Spine J 2021;21(4):708–19.
[27] Patwardhan AG, Havey RM, Meade KP, Lee B, Dunlap B. A follower load increases the load-carrying capacity of the lumbar spine in compression. Spine 1999;24(10):1003–9.
[28] Bland JM, Altman DG. Multiple significance tests: the Bonferroni method. BMJ 1995;310(6973):170.