

## Original Article

# Biomechanical study of rod stress after pedicle subtraction osteotomy versus anterior column reconstruction: A finite element study

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## Abstract

**Background:** In an effort to minimize rod fractures and nonunion in pedicle subtraction osteotomy (PSO) constructs, surgeons have adopted multirod constructs and interbody cages. Anterior column realignment (ACR) with posterior column osteotomies is a minimally invasive alternative to PSO in sagittal balance correction, however, there is a paucity of evidence with respect to rod survival.

**Methods:** Three-dimensional (3D) finite-element-model of a T12-sacrum spine segment was used to compare a 25° PSO at L3 and an ACR with a posterior column osteotomy and 30° hyperlordotic interbody cage at L3–4. The amount of overall T12–S1 lordosis correction was the same for each condition. Each simulation included cobalt chromium alloy primary rods with: (1) PSO; (2) PSO with an interbody cage (IB) at L2–3 (PSO+IB); (3) PSO with accessory (A) rods and IB at L2–3 (PSO+IB+A); (4) PSO with satellite (S) rods and IB at L2–3 (PSO+IB+2S); (5) ACR; (6) ACR with satellite rods (ACR + 2S). A 400 N follower preload was simulated for each condition.

**Results:** PSO condition had the largest rod stress of 286 MPa in flexion. Adding interbody support reduced the rod stress by 15%. The 4-rod constructs further reduced rod stress, with the satellite rod condition facilitating the largest reduction. The rod stress in the ACR+2S was equivalent to the PSO+2S, with 50% reduction in rod stress.

**Conclusion:** The rod stress with an ACR was comparable to a PSO coupled with interbody support. These results suggest an ACR is a viable MIS alternative to a PSO without the need for a large posterior osteotomy.

**Key Words:** Anterior column realignment, finite element analysis, MIS, pedicle subtraction osteotomy, rod fracture

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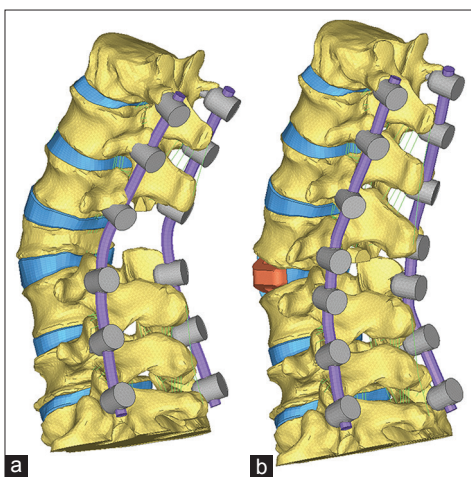
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## INTRODUCTION

Pedicle subtraction osteotomies (PSOs) can enable significant corrections of alignment in adult deformity surgery, yielding 25–40° of lordosis at a single level depending on the technique.<sup>[1,4]</sup> Though time-tested, PSO is associated with well-documented complications and morbidity.<sup>[5,7]</sup> One of the more frequent complications is rod fracture and subsequent nonunion due to the significant rod contouring required.<sup>[3]</sup> To reduce rod fractures, surgeons have evaluated techniques such as interbody cages adjacent to the PSO and addition of supplemental rods to the construct.<sup>[6]</sup> Minimally invasive methods to address sagittal imbalance, such as anterior column realignment (ACR) incorporating anterior longitudinal ligament release and hyperlordotic interbody cages, have been recently introduced to avoid complications related to a large osteotomy such as PSO.<sup>[2,8,9]</sup> The relative novelty of ACR, however, means there is limited clinical evidence with respect to rod survival rates. The purpose of this study is to use finite element analysis (FEA) to compare rod stress across different PSO and ACR construct combinations, where rod stress serves as a predictor of rod fracture.

## MATERIALS AND METHODS

A nonlinear three-dimensional (3D) finite element model of a T12-sacrum spine segment was created using geometric data derived from computed tomography (CT) scan of a cadaveric spine.<sup>[6]</sup> The geometry of the spine model and the material properties of each tissue taken were meshed using Hypermesh (Altair, Troy, MI) in a combination of tetrahedral elements for the vertebrae and hexahedral elements for the intervertebral discs and ligaments, as described in previously reported literature [Figure 1].<sup>[3]</sup>



**Figure 1: Finite element mesh of the PSO (a) and ACR (b) models stabilized with pedicle screws and primary fixation rods only. PSO denotes pedicle subtraction osteotomy; ACR, anterior column realignment**

The geometry was modified to approximate a 25° PSO at L3 or an ACR with a 30° interbody cage and Smith-Petersen osteotomy (SPO) at L3–L4. Each condition had the same degree of lordosis restoration over the T12–S1 segment. The osteotomies were created by removing all the posterior elements of L3 using a 25° wedge and then closing the osteotomy. Cobalt chromium alloy bilateral rods with segmental fixation, classified as primary rods, ranged T12–S1. The presence of supplemental rods across the index level was classified as follows: accessory rods, which were connected to the primary rods via cross-connectors, or satellite rods, which were independently anchored to the adjacent vertebrae.

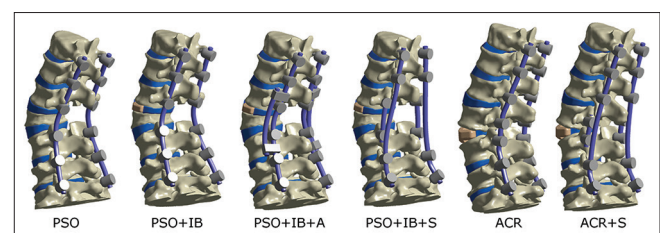
### Model validation

The stiffness of each spinal motion segment in the primary loading directions (flexion-extension, lateral bending, and axial rotation) is primarily controlled by the material properties of the intervertebral disc and spinal ligaments. The intact, uninstrumented spine model was validated by comparing the segmental stiffness of the model with experimental *in-vitro* results from literature.<sup>[12,21,23-25]</sup> Due to the variation in boundary conditions among studies, rotational segment stiffness was used to allow equivalent comparisons. The results from the finite element model were within ranges reported in the literature.

### Test conditions

A 400 N follower preload combined with unconstrained pure 7.5 N·m moments in flexion, extension, lateral bending, and axial rotation was applied to the superior endplate of T12. The sacrum was restricted from all motions via rigid anchors. A pure moment was used to load the model as it has two primary advantages: it is independent of spinal geometry as the applied moment on the proximal vertebrae is applied equally to all segments in the spine and the pure moment remains unchanged as the spine deforms during testing.<sup>[10,11]</sup> Six conditions were evaluated [Figure 2]:

1. PSO construct with bilateral primary rods from T12–S1 (PSO)
2. PSO with an interbody cage (IB) at L2–L3 and bilateral primary rods from T12–S1 (PSO+IB)
3. PSO with an interbody cage at L2–L3, primary rods from T12–S1, and bilateral accessory rods (A) spanning L1–L2 to L4–L5 (PSO+IB+A)



**Figure 2: Oblique view of each T12-S1 deformity reconstruction. PSO denotes pedicle subtraction osteotomy; IB, interbody; A, 2 accessory rods; S, 2 satellite rods; ACR, anterior column realignment**

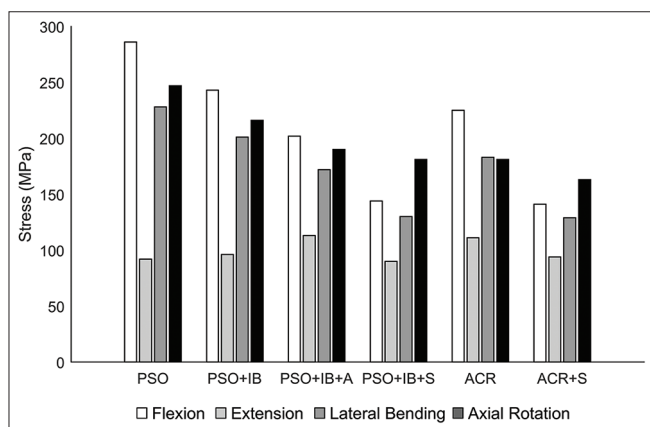
4. PSO with an interbody cage at L2–L3, primary rods from T12–S, and bilateral satellite rods (S) from L2–L4 (PSO+IB+2S)
5. ACR construct with a 30° interbody cage L3–L4 and bilateral primary rods from T12–S1 (ACR)
6. ACR construct with a 30° interbody cage L3–L4, bilateral primary rods from T12–S1, and bilateral satellite rods from L3–L4 (ACR+S).

The von Mises stress distribution in the primary and supplemental rods under maximum load (7.5 N·m) was calculated for each test construct in each loading direction. Maximum rod stress was determined.

## RESULTS

The largest rod stress of 286 MPa was observed with the PSO construct under the flexion loading condition [Table 1; Figure 3]. The stress concentration occurs at the acute bend in the rod, with sharp contouring required to match the curvature of the spine [Figure 4]. Comparing against other conditions in flexion, addition of interbody support to the PSO (PSO+IB) reduced the rod stress by 15%. In a 2-rod construct, accessory rods (PSO+IB+A) reduced the rod stress from the PSO condition by 29% whereas satellite rods (PSO+IB+S) facilitated the largest reduction in primary rod stress, reducing it by 50%. The 4-rod constructs had less stress than the 2-rod constructs. The rods stress was reduced by 21% with an ACR, 50% for PSO with interbody support and satellite rods, and 51% for ACR with satellite rods. The rod stress in the ACR with satellite rods was equivalent to the PSO with interbody support and satellite rods, each with a 50% reduction in rod stress compared to PSO.

In extension, the rod stress for a PSO was 92 MPa. The PSO+IB and PSO+IB+A conditions, respectively, resulted in 4% and 23% increases in stress. The ACR



**Figure 3: Maximum von Mises stress on the primary rods for each test condition and loading direction. PSO denotes pedicle subtraction osteotomy; IB, interbody; A, 2 accessory rods; S, 2 satellite rods; ACR, anterior column realignment**

condition resulted in a 21% increase in stress compared to PSO. The satellite rod condition resulted in the smallest changes in stress, with the PSO+IB+S having a 2% decrease, while the ACR+2S had a 2% increase in stress relative to a PSO under 7.5 N·m of extension.

In lateral bending, the rod stress for a PSO was 228 MPa. The PSO+IB and PSO+IB+A conditions, respectively, resulted in 12% and 25% decreases in stress. The ACR condition resulted in a 20% decrease in stress. The satellite rod condition resulted in equivalent changes in stress, with the PSO+IB+S and ACR+2S each having a 43% decrease in stress.

In axial rotation, the rod stress for a PSO was 247 MPa. The PSO+IB and PSO+IB+A conditions, respectively, resulted in 12% and 23% decreases in stress. The ACR condition resulted in a 27% decrease in stress. The satellite rod condition resulted in decreased stress by 27% for the PSO+IB+S condition and by 34% for the ACR+2S condition.

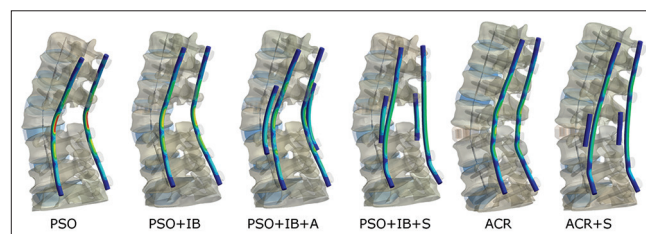
## DISCUSSION

Prior studies and cadaveric investigations demonstrated that sagittal correction with an ACR and posterior column osteotomies was comparable to that of a PSO.<sup>[13,26,27]</sup> Pedicle screw fixation two levels above and below the interbody has been shown to provide

**Table 1: Maximum von Mises stress in primary rods with respect to the PSO condition. Actual stress values shown for PSO condition, percent difference from PSO shown for others**

Test Condition	Flexion	Extension	Lateral Bending	Axial Rotation
PSO	286 MPa	92 MPa	228 MPa	247 MPa
PSO+IB	-15 %	4 %	-12 %	-12 %
PSO+IB+A	-29 %	23 %	-25 %	-23 %
PSO+IB+S	-50 %	-2 %	-43 %	-27 %
ACR	-21 %	21 %	-20 %	-27 %
ACR+S	-51 %	2 %	-43 %	-34 %

PSO: Pedicle subtraction osteotomy; IB: interbody; A:2 accessory rods; S: 2 satellite rods; ACR:Anterior column realignment



**Figure 4: Maximum von Mises stress contour plots for each rod. The stress scaling is the same for all images (0-300 MPa). Geometric scaling is also identical, however ACR is a lengthening procedure. PSO denotes pedicle subtraction osteotomy; IB, interbody; A, 2 accessory rods; S, 2 satellite rods; ACR, anterior column realignment**

adequate biomechanical stabilization.<sup>[14]</sup> Traditional PSOs have been supplemented with a variety of construct techniques to help improve their biomechanical stability and minimize rod fracture. One such technique is the use of cobalt chrome rods over traditional titanium rods. Another technique is the use of accessory rods or satellite rods that bridge across the PSO.<sup>[14-16,28]</sup> Lastly, some surgeons have supplemented with an interbody cage at the superior disc space of the PSO to create a longer fusion construct and lessen the long-term burden on the rods.<sup>[11]</sup>

The highest rod fracture rates reported in literature are with the classic PSO techniques, and the lowest reported are those with satellite rods and interbody supplementation.<sup>[14,15,2,17]</sup> This was consistent with the results of our FEA study. Rod failure is thought to result from stress-fatigue due to the severe angulation required to maintain a great degree of lordosis. Several studies have shown that rod bending creates notches and stress concentrations as the rod contours; thus, decreasing fatigue resistance.<sup>[18,19]</sup> Performing a PSO forces the load to be placed posteriorly on the osteotomy rather than be shared between the vertebral bodies and the posterior column like in an intact spine.<sup>[20]</sup> This inevitably places significantly more stress on the rod at the PSO level leading to decreased fatigue resistance and early instrumentation failure.

In our FEA study, we compared four PSO constructs and analyzed the mechanical stress on the rods for each one. Alternative physical methods to study rod loading, such as strain gages, only provide strain information at discrete gage locations. A finite element model is advantageous as it provides the stress distribution along the entire rod and eliminates specimen variability. A PSO model representing 25° of lordosis at L3 was used for all constructs. A PSO without an interbody showed the highest stress on the rods, and this stress was minimized somewhat by adding an interbody at the superior disc space. A PSO with interbody and accessory rods further minimized rod stress, however, the biggest reduction in stress was achieved in a PSO model with an interbody and two satellite rods. Use of multirod system versus a 2-rod system has been previously described in successfully minimizing instrumentation failure at the osteotomy site as well as the rates of pseudoarthrosis,<sup>[15,22]</sup> therefore, the trends predicted by our model appear to be supported by clinical findings, validating this finite element model.

The mechanical stress reduction of an ACR with satellite rods was equivalent to a PSO interbody construct with satellite rods (PSO+IB+S), both reducing rod stress by 50% in flexion. The mechanical stress of an ACR without satellite rods was 21% less than that of the classic PSO but still 8% higher than that of a PSO interbody construct with accessory rods (PSO+IB+A) in flexion loading.

Interestingly, when comparing a PSO with interbody support (PSO+IB) and primary rods with an ACR without satellite rods, the difference was only 6% (15% vs. 21% stress reduction, respectively). The results of our FEA show that the ACR may have a biomechanical support advantage over the un-supplemented PSO and that both supported with satellite rods may be comparable in rod stress reduction. It is yet to be determined if these constructs have equivalent clinical benefit in terms of hardware failure and pseudoarthrosis rates.

Complex spinal deformities can accurately be reconstructed and studied using FEA, with loading conditions similar to that of cadaveric studies. Such models are a good option for predicting possible clinical outcomes in hard to design or lengthy case-control studies or randomized trials. Results from FEA can be used to design even better clinical studies to follow as they cannot completely account for all components effecting mechanical behavior of the spinal column. Gravity, postural control by the muscular system, and the effect of demographics, age, and race were not considered and may affect the analysis. Conclusions from finite element studies cannot be directly correlated clinically, but can be a good predictor of trends that may correlate with clinical outcomes and provide an impetus for further investigation.

There are several important limitations of our study. We did not address a difference in rigidity of different kinds of rods. Stress reductions may differ depending on whether cobalt-chromium, titanium, or steel alloy rods are used. In addition, rod fracture occurs after cyclic loading which creates an alternating stress on the rod. Because we did not perform cyclic loading, it is not possible to tell how soon the rod would fracture or predict the clinical risk of instrumentation failure. It is possible that our results would be magnified or changed over time with cyclic loading analysis. While the timing issue through cyclic loading was not addressed, the invaluable information of stress reduction with supplemental rods or alternative techniques such as MIS ACR cannot be overlooked. The challenge of creating rod fractures in a cadaveric model has been demonstrated previously,<sup>[11]</sup> thus FEA may provide an alternative and more feasible, method to predict the risk of rod fracture based on relative stress magnitudes. Creation of notches through rod bending, which may generate stress concentrations and adversely affect fatigue strength of the construct, was also not addressed. Stress and strain analysis at adjacent segments, other spinal structures or implants was also not performed but would be interesting to evaluate in future studies, as it may add additional information regarding instrumentation failure mechanism. Difference in instrumentation failure in PSO vs. ACR multi-rod constructs is yet to be determined clinically, and is currently under way.



## CONCLUSION

FEA showed significant (50% in flexion) primary rod stress reduction in a PSO with interbody and 4-rod satellite construct compared to a PSO without interbody and 2-rod construct, which may reduce risk of rod fracture *in vivo* with the 4-rod construct. Interestingly, ACR with a 4-rod satellite construct had comparable stress reduction to the PSO 4-rod satellite construct in all loading directions. ACR with a 4-rod construct is an excellent MIS alternative to a more morbid surgery requiring large osteotomies. This FEA needs to be further confirmed in a clinical scenario in a prospective study and long-term follow up, which is currently under way.

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Nil.

## Conflicts of interest

There are no conflicts of interest.

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