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BIOMECHANICS

Does the anterior column realignment technique influences the stresses on posterior instrumentation in sagittal imbalance correction? A biomechanical, finite-element analysis of L5–S1 ALIF and L3–4 lateral ACR

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Abstract

Study design Biomechanical finite-element study.

Objective To directly compare the biomechanical effects of two different techniques for sagittal plane correction of adult spine deformity based on the anterior longitudinal ligament (ALL) resection and use of hyperlordotic cages, namely, the anterior column realignment (ACR) in L3–4, and ALIF in L5–S1 in terms of primary stability and rod stresses using finite-element models.

Methods A finite-element model of the thoracolumbar spine was used to perform the analysis. Starting from this "intact" model, three further models were constructed through the insertion of spinal instrumentation, i.e., pedicle screws, rods and cages:
1) posterior instrumentation between T9 and S1 (referred to as "T9-S1");
2) posterior instrumentation T9–S1 + Hyperlordotic (26°) ALIF cage in L5–S1 ("ALIF");
3) posterior instrumentation T9–S1 + Hyperlordotic (30°) ACR cage in L3–4 ("ACR").
These models were studied by simulations applying, alternately, a pure moment of 7.5 Nm between the three planes of motion (flexion, extension, lateral bending, and bilateral axial rotation), uniformly distributed over the upper surface of the T9 thoracic vertebra. A total of 24 simulations were performed (6 per models).

Results All models presented a significant reduced ROM when compared to the intact model; the ROM reduction was higher both at L3–4 in the ACR model and at L5–S1 in the ALIF model. At L3–4, the ACR model had, in all cases, the lowest maximum values of Von Mises stresses on the rods, especially in flexion–extension. At L4–5, the ALIF model had the lowest stresses during flexion–extension and axial rotation, while the ACR model had the lowest stresses during lateral bending. At L5–S1, the ALIF model had, in all cases, the lowest stresses on the rods.

Conclusions This finite-element study showed how both ACR at L3–4 and ALIF–ACR at L5–S1 are effective in restoring lumbar lordosis (LL), stabilizing the spine and reducing stress on posterior rods at the index level when compared to a simple fixation model. Interestingly, ALIF–ACR reduces rod stress even at L4–5 in flexion–extension and axial rotation, possibly due to a better distribution of LL, especially on the lower arch, while ACR reduces the stress at L4–5 in lateral bending, possibly thanks to the larger footprint of the cage that increases the area of contact with the lateral side of the endplates.

Keywords ALIF · ACR · Sagittal balance · Finite elements

Introduction

In adult spinal deformities (ASD), correction of the Sagittal Imbalance is the main surgical goal. It is well-recognized that postoperative disabilities and mechanical failures have been attributed to inadequate restoration of the sagittal

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profile [1]. Therefore, when planning a surgery on a patient with severe sagittal deformity, surgeons have several technical options that can be used to restore the normal spinal alignment, mainly acting on lumbar lordosis (LL). While the tricolumnar osteotomy such as the pedicle subtraction osteotomy (PSO) offers a huge corrective power, this technique highly destabilizes the spine leading to a high rate of pseudoarthrosis and implant failures [2]. Thus, in the last few years different anterior realignment techniques were described. Among those, anterior column realignment (ACR) was recently proposed as an alternative to the PSO to correct sagittal imbalance caused by lumbar disc degeneration. The ACR procedure consists of lateral trans-psoas approach to perform complete discectomy and release of both the anterior longitudinal ligament (ALL) and annulus. After the release, hyperlordotic interbody cages are positioned into the disc space and fixed between the vertebral bodies. Given the presence of the iliac wings that limits the possibility to approach L5–S1 disc, the most common discs involved are L4–5 and L3–4. This approach offers a corrective power similar to the PSO, while being linked with fewer complications [3]. A third, different approach is the realignment through the L5–S1 anterior lumbar interbody fusion (ALIF) coupled with posterior column osteotomies. This technique shares with the ACR the anterior release of the ALL and the combination of anterior and posterior correction, therefore, is often called ALIF–ACR [4].

Given the relative novelty of such means of sagittal imbalance correction, few evidence exists regarding the stresses on the posterior instrumentation with different techniques. Previous papers showed how the ACR in L3–4 generates a rod stress comparable to the PSO with interbody support [5]. However, no studies directly compared the rod stresses with correction performed between ACR and ALIF–ACR.

The aim of this study is to compare the biomechanical effects of ACR in L3–4 and ALIF in L5–S1 in terms of primary stability and rod stresses using finite-element models.

Methods

Finite-element models and spinal instrumentations

To perform the analysis, a finite-element model of the thoraco-lumbar spine was used, which was described in a previous study [6]. Starting from this "intact" model, further models were built through the insertion of spinal instrumentation, namely, pedicle screws, spinal rods and intervertebral cages: (1) pedicle screws and posterior rods between T9 vertebra and S1 vertebra in the sacrum ("T9-S1"); (2) pedicle screws and posterior rods between T9 vertebra and S1 vertebra in the sacrum, and intervertebral cage in L5–S1 ("ALIF"); (3) pedicle screws and posterior rods between T9 vertebra and S1 vertebra in the sacrum, and intervertebral cage in L3–L4 ("ACR").

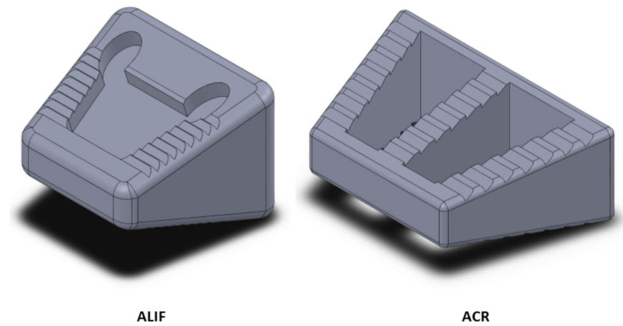

Fig. 1 Three-dimensional models of the two hyperlordotic cages: ALIF (left) and ACR (right)

Three-dimensional geometrical models of pedicle screws, spinal rods and intervertebral cages were designed in Solidworks (Solidworks Corp., Waltham, MA, USA). Spinal rods had a diameter of 5.5 mm. A pedicle screw with a length of 45 mm and a diameter of 6 mm was used as a reference. Two different, commercially available cages were used as a reference for modeling (Fig. 1):

- hyperlordotic titanium cage with lordotic correction angle of 26 degrees was used in ALIF (Sahara, Stryker, Kalamazoo, Michigan, USA);
- hyperlordotic titanium cage with a different lordotic correction angle of 30 degrees was used to perform ACR (CoRoent XL hyperlordotic, Nuvasive Inc., San Diego, California).

All implants were modeled as having the material properties of titanium (elastic modulus of 110 GPa and Poisson's ratio of 0.3) and discretized using linear tetrahedral elements.

Boundary conditions and interactions

Simulations were carried out by applying, alternatively, a 7.5 Nm pure moment among the three motion planes (flexion, extension, left and right lateral bending, left and right axial rotation), which was uniformly distributed on the upper surface of T9 thoracic vertebra. All nodes belonging to the sacrum were constrained in the finite-element models to simulate a zero displacement of this bone structure. A total of 24 simulations were performed (6 simulations for each models).

The relative contacts between screws, cages and bone as well as contacts between screws and rods were created. Embedded elements were used to define the contact between pedicle screws and vertebral bones simulating zero displacements between these two components of the models. Tie constrains were used to define the contact between intervertebral cages and vertebral bones, as well as between rods and pedicle screws simulating no displacements among these components of the models.

Model metrics

Results were obtained by running the simulation through Abaqus CAE 2018 software (Dassault Systemes, Simulia, Johnston, RI, USA).

First, a validation of the intact model was done by comparing the range of motion (ROM) from L1 to S1 vertebra obtained by the finite-element model and the corresponding values found in literature [Cook]. After the validation, a quantitative comparison among the three instrumented models was performed in terms of relative ROM between T9 to S1 vertebra with respect to the intact model and of maximal stress on the posterior rods for three different regions: L3–4, L4–5, and L5–S1.

Results

Validation of the intact model

L1–S1 ROMs were within the standard deviation of the values found in literature [7] for all three loading conditions, except for ROM between L1 and L2 vertebra in axial rotation (Fig. 2). According to this, the validation of the intact finite-element model was supported by the in vitro study of Cook [7].

Range of motion

Compared to the intact model, T9–S1 had significantly lower ROM values in all the spinal segments considered in flexion–extension, lateral bending and axial rotation (Fig. 3). The two other instrumented configurations (ALIF and ACR) demonstrated a behavior similar to T9–S1 with respect to the intact model, except for some values; L3–4 ROMs strongly decreased when ACR was performed with respect to T9–S1 and ALIF (up to 3% of the intact value in lateral bending), and up to 99.9% of the intact value in lateral bending with respect to the intact model, increasing the stability of this region. The same thing happened for L5–S1 ROMs when ALIF was performed; nevertheless, a decrease up to 99.6% of the intact values was found in flexion–extension. With respect to T9–S1 and ACR, L5–S1 ROMs showed, respectively, a decrease up to 9.4% and 10% of the intact value in axial rotation.

Von Mises maximum rod stresses: L3–4

Due to the symmetry of the model, Von Mises maximal stresses on the rods for the L3–4 spinal segment were

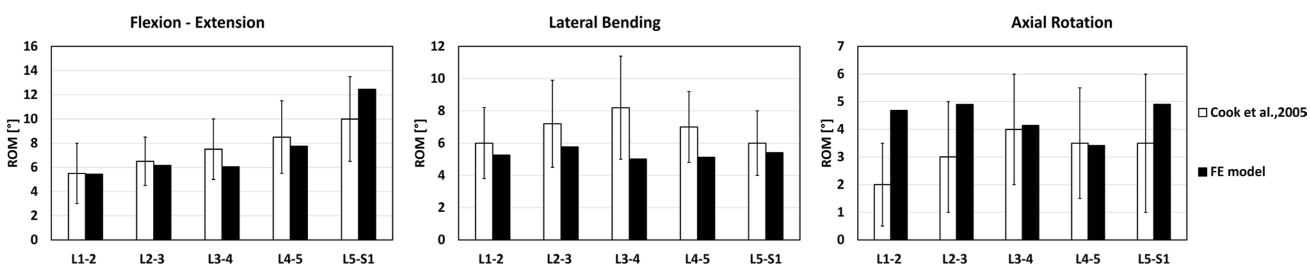

Fig. 2 Ranges of motion in flexion–extension, lateral bending and axial rotation calculated with the present intact model ("FE model") as compared with in vitro data from the literature [Cook]

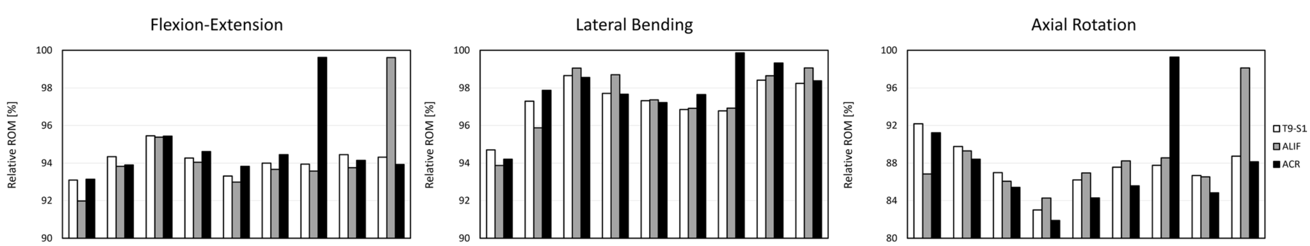

Fig. 3 Relative reduction in the range of motion (flexion–extension, lateral bending and axial rotation) with respect to the one calculated with the intact model for the three instrumented models (T9–S1, ALIF, ACR)

reported only for the left posterior rod; values on the right posterior rod showed similar results (Fig. 4).

Among all the considered movements, a common pattern can be easily highlighted, namely, that the ACR model had, in all cases, the lowest maximum values of Von Mises stresses. This discrepancy between the maximum stress values of the latter model with respect to T9–S1 and ALIF models was particularly significant in flexion–extension, while in lateral bending and axial rotation the maximum values were comparable among all the models.

Von Mises maximum rod stresses: L4–5

Due to the symmetry of the model, Von Mises maximal stresses on the rods for the L4–5 spinal segment were reported only for the left posterior rod; values on the right posterior rod showed similar results (Fig. 5).

In flexion–extension, the ACR model appeared to have the highest maximum stresses, although they were comparable with those of the T9–S1 model. On the other hand, the ALIF model had the lowest stresses. Nonetheless, in lateral bending the ACR model showed the lowest stresses, while the simple fixation model had the highest stress values, even if they were in same order of magnitude as those of the ALIF model.

In axial rotation, on the contrary, the ACR model had the highest maximum value of stress, significantly higher than the other two models.

Von Mises maximum rod stresses: L5–S1

Due to the symmetry of the model, Von Mises maximal stresses on the L5–S1 spinal segment were reported only for the left posterior rod; values on the right posterior rod showed similar results (Fig. 6).

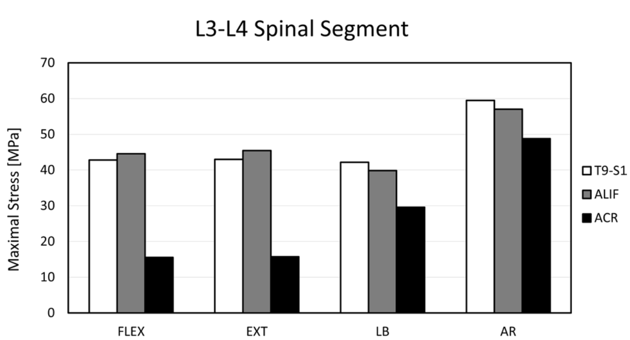

Fig. 4 Maximal stresses calculated in the left posterior rod in correspondence of the L3–L4 level for different loading scenarios (“FLEX”: flexion; “EXT”: extension; “LB”: lateral bending; “AR”: axial rotation)

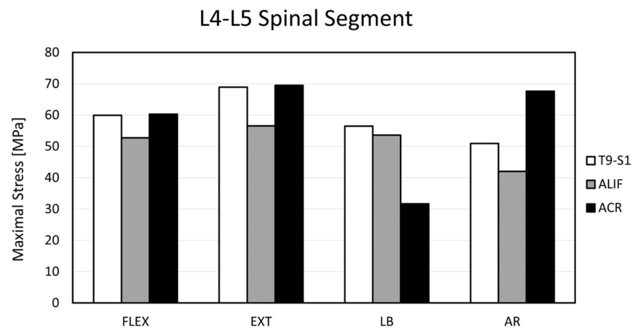

Fig. 5 Maximal stresses calculated in the left posterior rod in correspondence of the L4–L5 level for different loading scenarios (“FLEX”: flexion; “EXT”: extension; “LB”: lateral bending; “AR”: axial rotation)

A common pattern is observed in all the considered movements: the ACR model was the one with the highest maximum stresses, while the ALIF model had the lowest stresses, except for left lateral bending, where the maximum stress of the simple fixation model was lower than both ALIF and ACR stresses.

Discussion

In surgery for ASD, restoration of sagittal balance is the critical goal. While different techniques could be used to reach this goal, the rate of mechanical failures of the posterior instrumentation remains high, especially with Schwab Grade 3 osteotomies [8]. Ideally, a surgical technique for sagittal plane realignment should allow for LL restoration, should provide stability to the spine and induce the minimum stress on posterior instrumentation. In this paper, the stresses on the posterior spinal rods were evaluated and compared among two different techniques for anterior realignment of the sagittal plane, i.e., ACR at L3–4 and ALIF at

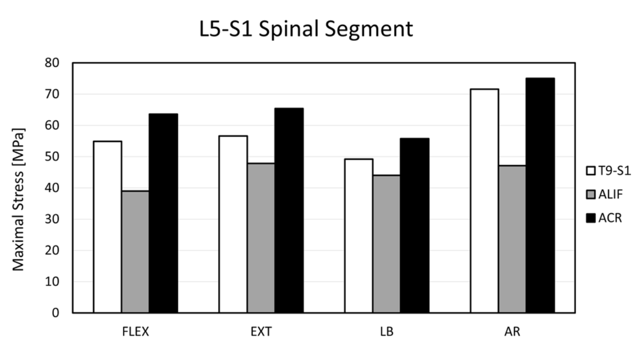

Fig. 6 Maximal stresses calculated in the left posterior rod in correspondence of the L5–S1 level for different loading scenarios (“FLEX”: flexion; “EXT”: extension; “LB”: lateral bending; “AR”: axial rotation)

L5–S1. The main finding of this study was that ACR reduces the stress on the posterior elements at L3–4 when compared to ALIF and simple fixation models, while ALIF is superior in reducing the stresses on the rods at L5–S1 level in all the tested movements and at L4–5 in flexion–extension and axial rotation.

Early biomechanical and feasibility studies on ACR focused on the theoretical destabilization of the spine following the release of the ALL. Indeed, the integrity of ALL is crucial for maintaining spinal stability in extension, and at lesser degree in axial rotation and lateral bending [9, 10]. The spinal instability due to ALL resection, either at L3–4 or at L5–S1, is, however, compensated by cage positioning, that increase stability through several mechanisms: first, the large footprint of the cage allows for an increased area of contact on the margin of the endplates, particularly on the posterolateral part, that is the most resistant to the axial loading [11]; second, the cages are hyperlordotic, and thus the anterior column is lengthened, increasing stability; third, most of the commercially cages are self-fixing either via plate or screws; finally, posterior fixation further increases the segmental stability [12]. These considerations are confirmed by ROM reduction observed in this study: the most relevant decrease was observed at the level, where the cage was placed in either model, i.e., at L3–4 in ACR an at L5–S1 in ALIF, with a reduction of 99% when compared to the intact models. Therefore, is it possible to conclude that both techniques significantly increase spinal stability despite ALL transection.

The most clinically relevant result of this paper is, however, the stress reduction on posterior elements. It is well-known that the most common type of mechanical failure of surgery in ADS is rod breakage. This complication occurs in 58% of patients at 5 years after surgery, and it is the most common cause of revision surgery [13]. Therefore, understanding how to reduce the mechanical stresses on rods is crucial to optimize surgical results. Previous biomechanical studies on ACR showed that this technique holds an advantage in terms of stress reduction on the rods when compared with Schwab grade 3 osteotomies such as PSO. Januszewski et al. in a finite-element models study, compared a 25° PSO at L3 with a 30° hyperlordotic ACR at L4; they found that ACR reduced rod stress of 50% in flexion, 43% in lateral bending and 37% in axial rotation when compared with the PSO model [5]. However, no previous study directly compared ACR at L3–4 with L5–S1 ALIF–ACR. In our model, we observed a significant reduction on rod stress at the level, where the cage was placed, namely, L3–4 in the ACR model and L5–S1 in the ALIF model, when compared to the posterior fixation model. This observation is consistent with previously reported results, that showed how cage placement reduce rod stress at the index level [5, 14]. Interestingly, with ALIF, we have observed a significant reduction of rod stress during axial rotation and flexion–extension also at L4–5 when compared with ACR model. This observation could be explained by the better lordosis distribution with ALIF, that acts on the lower arch of LL. Indeed, several studies showed how a better restoration of lordosis in the lower arch (L4–S1) and the lumbar apex reduces the risk of mechanical complications after sagittal plane realignment [15, 16]. On the contrary, ACR reduces the rod stress at L4–5 in lateral bending; this could be explained by the larger footprint of the cage, that has a greater area of contact with the lateral sides of the endplate.

The finite-element models presented in this study suffer from some technical limitations. First, only the intact model was validated against in vitro flexibility data [7], while for the instrumented models no analogous experimental data were available for direct comparison. A simplified modeling approach not allowing for any relative movement was used to simulate the interactions between instrumentation and bone, while it is well-known that some motion between pedicle screws and vertebrae takes place, especially in the sacrum [17]. Bone material properties referred to healthy bone tissue [6], whereas patients suffering from adult spinal deformities often show osteopenia or osteoporosis which were not taken into account in the present study. Besides, the applied loads did not replicate accurately the complex physiological loading environment, but were chosen to maximize standardization and comparability, based on published guidelines [18]. Simulating a more realistic loading scenario would lead to generally higher instrumentation stresses [19], but we expect that the comparative analysis between the instrumented models would not show large differences with respect to the results where reported. Finally, in this study the instrumented models did not include a cage in L4–5; the anterior and lateral approaches at this level are more at risk for serious complications, due to the vascular and nervous anatomy, and thus is a less performed approach [20, 21]; nonetheless, this aspect could be evaluated in further studies.

Conclusions

To the authors' knowledge, this is the first biomechanical study that directly compares two different techniques for sagittal realignment based on ALL resection and the use of hyperlordotic cages, namely, ACR at L3–4 and ALIF–ACR at L5–S1. The main findings of this paper can be summarized as follows:

- Both anterior realignment techniques evaluated are effective in restoring LL without destabilizing the spine, as showed by the ROM reduction, despite the resection of ALL.

- The use of anterior support reduces the stress on the rods at index level in all plane of movement evaluated, consistently with previous reports [14]
- The reduction of rod stress is particularly marked in flexion (and axial rotation for ALIF), despite the increase in LL at the index level, thanks to the protective effect of the cage.

Interestingly, ALIF reduces rod stress even at L4–5 in flexion–extension and axial rotation, possibly due to a better distribution of LL, especially on the lower arch, while ACR reduces the stress at L4–5 in lateral bending, thanks to the larger footprint of the cage that increases the area of contact with the lateral side of the endplates. Therefore, both techniques are effective in achieving their main goals (restoring LL, stabilizing the spine and protecting posterior elements of the instrumentation), but with different advantages. This work reinforce the data in favor of a patient's specific sagittal plane correction, with lordosis restored according to the Roussouly type; in this context, these data could be used as benchmark for the selection of the better correction technique for each patient.

Authors contributions MP: methodology (model computation); statistics; writing—original draft preparation, MB: methodology (model computation), TMTV: writing—critical review and editing; supervision, FG: methodology (model computation); writing—critical review and editing, MM: writing—original draft preparation, BM: writing—critical review and editing; supervision, EG: conceptualization; writing—original draft preparation. All authors declare that they read and approved the final version to be published and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Declarations

Conflict of interest All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Ethics approval The present work was approved by our Institutional Review Board. No ethical approval was needed for an 'in silico' study.

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