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Oblique, Unilateral, or Bilateral Rods Configurations for Single-Level Interbody Fusion and Posterior Spinal Fixation: A Finite Element Study

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ABSTRACT

AIM: To compare three different posterior mono-segmental instrumented models with a Lateral Lumbar Interbody Fusion (LLIF) cage in L4-L5 based on finite element (FE) analysis.

MATERIAL and METHODS: Three different configurations of posterior instrumentation were created: 1. Bilateral posterior screws with 2 rods: Bilateral (B); 2. Left posterior rod and left pedicle screws in L4-L5: Unilateral (U); 3. Oblique posterior rod, left pedicle screw in L4, and right pedicle screw in L5: Oblique (O). The models were compared regarding the range of motion (ROM), stresses in the L4 and L5 pedicle screws, and posterior rods.

RESULTS: The Oblique and Unilateral models showed a lower decrease in ROM than the Bilateral model (O vs U vs B; 92% vs 95% vs 96%). In the L4 screw, a higher stress level was identified in the O than in the B model. Still, lower if compared to U. In the L5 screw, the highest stress values were observed with the O model in extension and flexion and the U model in lateral bending and axial rotation. The highest stress values for the rods were observed for the O model in extension, flexion, and axial rotation and the U model in lateral bending.

CONCLUSION: The FE analysis showed that the three configurations significantly reduced the ROM. The stress analysis identified a substantially higher value for the rod and pedicle screws in oblique or unilateral configuration systems compared to the standard bilateral one. In particular, the oblique configuration has stress properties similar to the unilateral in lateral bending and axial rotation but is significantly higher in flexion-extension.

KEYWORDS: Single Rod fixation, Range of motion, von Mises stress, Degenerative disc disease, Anterior spinal approach

ABBREVIATIONS: LLIF: Lateral lumbar interbody fusion, **TLIF:** Transforaminal lumbar interbody fusion, **PLIF:** Posterior lumbar interbody fusion, **OLIF:** Oblique lumbar interbody fusion, **LLIF:** Lateral lumbar interbody fusion, **ALIF:** Anterior lumbar interbody fusion, **ROM:** Range of motion, **CBT:** Cortical bone trajectory, **3D:** Three dimensional, **FE:** Finite element

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INTRODUCTION

Lumbar interbody and posterior fusion can adequately address the vast majority of degenerative issues, such as lumbar instability, degenerative disc disease, spinal deformities, spondylolisthesis, recurrent disc herniation, and spondylodiscitis (13,18).

Circumferential fusion in the lumbar spine is nowadays the gold standard for its capacity to restore lordosis, enhance fusion and decompress the neurological structures. The number of spinal surgeries has significantly increased in the last decades, and it will likely further grow in the following years because of the ageing population (11), the consequent pursuit of a better quality of life (1), the future upcoming technological improvements and higher standard of care (19).

Several approaches are available to reach an interbody fusion (TLIF - transforaminal lumbar interbody fusion, PLIF posterior lumbar interbody fusion, OLIF - Oblique lumbar interbody Fusion, LLIF Lateral lumbar interbody Fusion, ALIF Anterior lumbar interbody Fusion) as well as there are multiple options to perform posterior elements fixation: free-hand, percutaneous, navigated or robotic pedicle screws with bilateral or unilateral fixation cortical bone trajectory (CBT) screws and even no posterior fixation (stand-alone cages). The ultimate choice relies on the patient's specifics, the surgeons' preference and the need for direct or indirect decompression (4,16).

The numerous studies comparing the different surgical options have not proven a definitive superiority of one technique over the others. However, LLIF (and OLIF - Oblique lumbar interbody Fusion) seems to allow the implant of the largest cages compared to other methods. These cages are bicortical and stand on the ring apophysis: the strongest part of vertebral endplates. Therefore, this reflects the decreased risk of subsidence, major stability of the cage and a higher chance of interbody fusion. As a result, this technique empowers indirect decompression (when feasible and desirable), avoiding unnecessary manipulation of neurological structures and the consequent risks. One limitation of LLIF and OLIF is the need for an anterior approach that presents its risks and increases operation time. However, there is an emerging interest in performing LLIF in the prone position (pro-XLIF) (9), avoiding the issues of repositioning the patient or performing posterior instrumentation in a lateral position.

Once the cage is appropriately placed in the intervertebral disc, posterior fixation significantly decreases the range of motion of the addressed level, promoting fusion and reducing the risk of implant failure. Pedicle screws require an accurate placement to avoid neurological issues; therefore, this procedure can be challenging, especially in scoliotic patients with small pedicles. To enhance the accuracy of pedicle screws, fluoroscopic navigation is often used, especially in minimally invasive cases (3,10). The main drawback of percutaneous screws is that they require x-rays responsible for an increased number of cancer cases and stochastic effects among personnel exposed to radiation. Unilateral fixation (2 pedicle screws instead of 4) can be performed with promising results to reduce radiation exposure and operation time. For the same reason, we decided to analyze two different types of posterior instrumentation consisting of two screws placed on opposite side pedicles connected with an oblique rod (oblique model) and two screws placed on the same side combined with a unilateral rod (unilateral model).

Considering the bilateral pedicle fixation as the gold standard in terms of stability, we hypothesize that oblique instrumentation should provide similar strength to the bilateral fixation and more homogeneous mechanical stress distribution than unilateral instrumentation. This rod configuration should theoretically provide half the radiation exposure and reduce the operative time if compared to the gold standard.

The study aims to compare three different posterior monosegmental instrumented models with an LLIF cage placed in L4-L5 based on a three-dimensional (3D) finite elements (FE) analysis:

1- left and right pedicle screws and rods in L4 and L5 ("bilateral")

2- only left L4 and L5 pedicle screws with a single left rod ("unilateral")

3- oblique rod connected to left L4 and right L5 pedicle screws ("oblique")

MATERIAL and METHODS

Finite Elements Models

The body model from the AnyBody Managed Model Repository (AMMR, version 2.0.0) in the standing position was used to construct a three-dimensional (3D) finite elements (FE) model of the osseous T10-pelvis spine. Intervertebral discs were created by extruding the surfaces of the vertebral endplates. The ligaments were modelled by using nonlinear springs. The material properties of the bones, intervertebral discs and ligaments were obtained with a calibration procedure based on data reported in the literature (21). A more detailed description and validation of this intact model are reported elsewhere (2).

Three different instrumented models were created from the intact FE model: 1) bilateral posterior screws in L4-L5 and LLIF cage between the vertebra L4 and the vertebra L5 ("Bilateral"); 2) left posterior rod and left pedicle screws in L4-L5, and LLIF (Lateral lumbar interbody fusion) cage between the vertebra L4 and the vertebra L5 ("Unilateral"); 3) oblique posterior rod, left pedicle screw in the L4 vertebra, and right pedicle screw in L5 vertebra, and LLIF cage between the vertebra L4 and the vertebra L5 ("Oblique") (Figure 1).

Boundary Conditions and Instrumentation

Pure moments of 7.5 Nm in extension, flexion, lateral bending, and axial rotation were applied to the upper endplate of T10 through a set of rigid beam elements. The acetabula were completely fixed by constraining all nodes belonging to the bilateral acetabula of the finite element models. Each model was used to run six simulations according to different loading directions. A total of 24 simulations (including the intact model) were run.

In all instrumented models, rods and screws were represented with 3D elements. Rods had a circular section with a diameter of 5.5 mm. Pedicle screws had a length of 45 mm and a diameter of 6 mm. The LLIF cage was 45 mm in length, 18 mm in width, 8 mm in height, and had a lordotic angle of 10 degrees. The instrumentation was modelled in titanium with an elastic modulus of 110 GPa and a Poisson coefficient of 0.3. As for the biological structures of the intact model, the pedicle screws, the rods, and the cage of the instrumented models were discretized using linear tetrahedral elements.

Pedicle screws were inserted into the bones by simulating embedded elements between these two structures. The interaction between the head of the pedicle screws and rods was modelled using a tie constraint, tying two separate surfaces. The tie constraint was also used to simulate the cage's contact with the lower endplate of the L4 vertebra and with the upper endplate of the L5 vertebra. In this way, any relative displacements between the instrumentation and bone were not allowed.

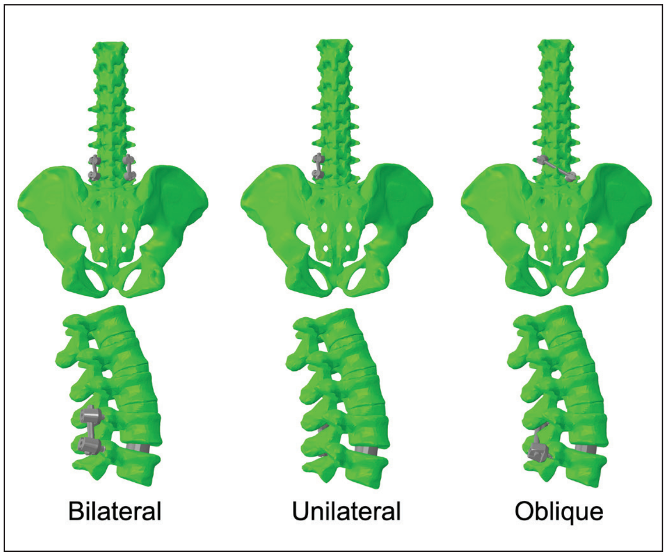

Figure 1: Spine models tested in this study in posterior and lateral views. **Bilateral:** bilateral posterior screws and 2 rods with interbody LLIF cage. **Unilateral:** left posterior rod and left pedicle screws in L4-L5 with interbody LLIF cage. **Oblique:** oblique posterior rod, left pedicle screw in the L4 vertebra, and right pedicle screw in L5 vertebra with LLIF cage.

Output and Comparison

A comparison in terms of ROM between the vertebra L1 and the vertebra L5 was made among the four models (intact, bilateral, unilateral, and oblique models) to evaluate the spine stability for each model.

A comparison in stresses in the pedicle screws (in L4 and L5) and the rods were made among the three instrumented models (bilateral, unilateral, and oblique models) to evaluate the risk of implant failure.

RESULTS

Validation and ROM

The ROMs calculated with the intact FE model were validated in another study (2). Among the four (intact, bilateral, unilateral, and oblique) models, negligible differences were found for the ROMs between two consecutive vertebrae, except for L4-L5, for the three motion planes (Figure 2).

The L4-L5 ROM showed that adding instrumentation at this level significantly increased the stability; decreases up to 92%, 95%, and 96% of the intact value were observed, respectively, in flexion-extension and lateral bending and axial rotation for the bilateral model (Figure 2).

When only two pedicle screws and one rod (unilateral and oblique models) were used, a lower decrease of the ROMs between L4-L5 was observed with respect to the bilateral model; for instance, a decrease up to 86% of the intact value was found in flexion-extension for the unilateral model (Figure 2).

Comparing the ROMs at L4-L5 between the unilateral and oblique models, minor differences were found for the three motion planes, especially for lateral bending (0.08°) and axial rotation (0.02°). For flexion-extension, a bigger but still negligible difference (0.3°) was calculated (Figure 2).

Stresses in the L4 Pedicle Screws

Stresses for left and right lateral bending and left and right axial rotation were found to be equal due to the model's symmetry. For this reason, only the stresses for left lateral bending and axial rotation were reported.

In extension, flexion, lateral bending, and axial rotation, the maximum stresses on the L4 pedicle screws were highest for the unilateral model (Figure 3, Figure 4).

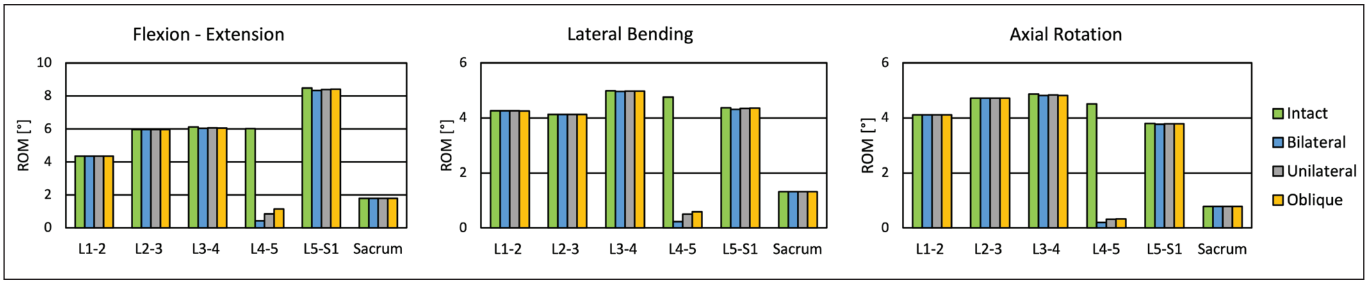

Figure 2: Comparison of the global range of motion (degree) of uninstrumented spine and three rod configurations (bilateral, oblique and unilateral) under flexion-extension, lateral bending and axial rotation.

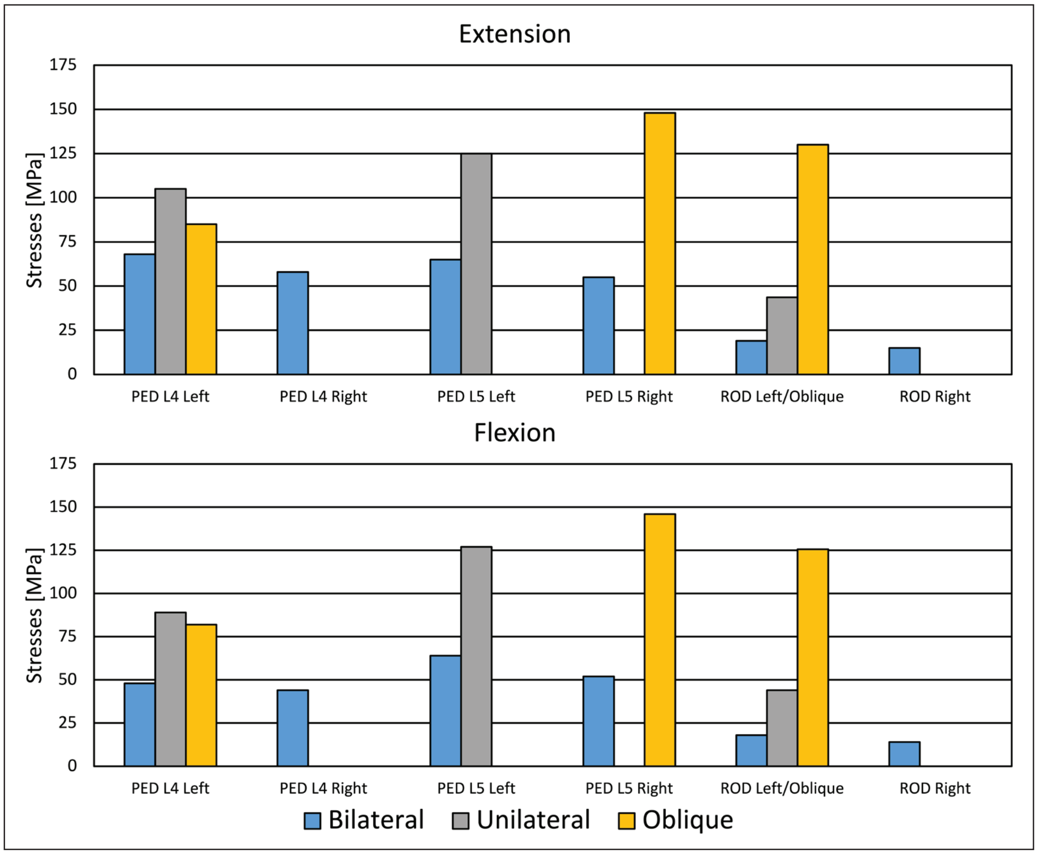

Figure 3: Comparison of the implants von Mises stress (MPa) of three models configurations under flexion and extension. **PED:** Pedicle screw; **ROD:** rod.

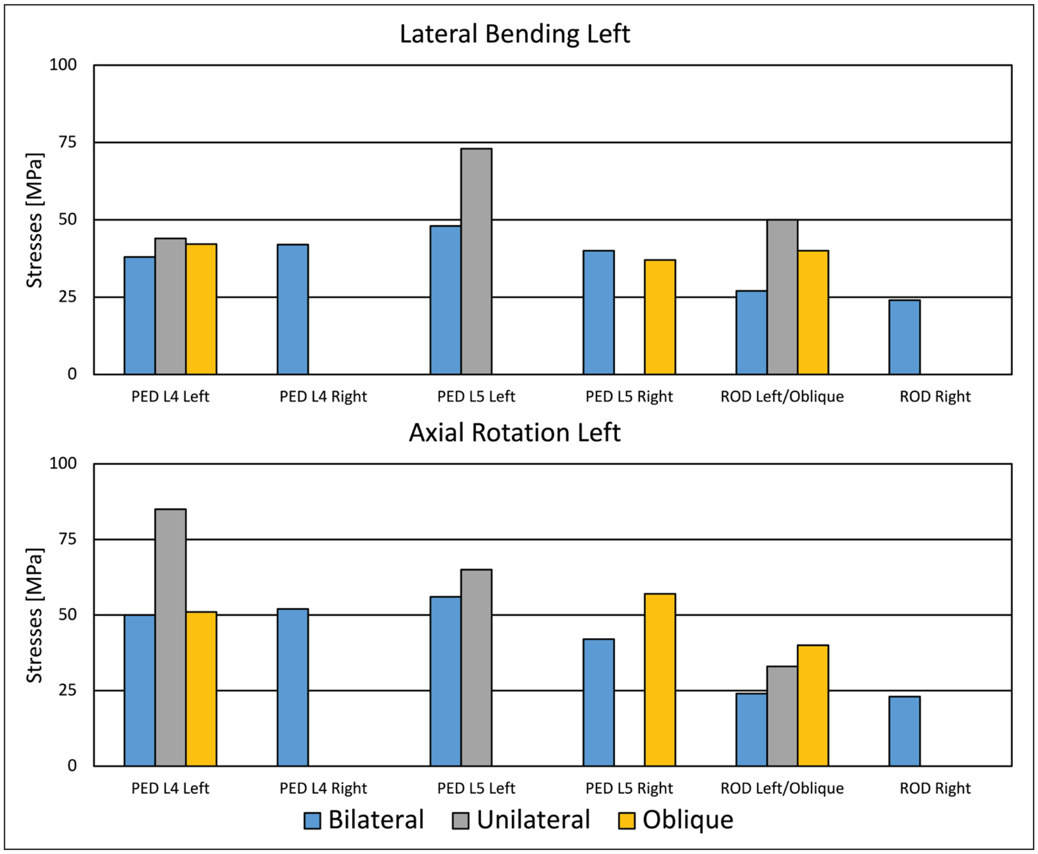

Figure 4: Comparison of the implants von Mises stress (MPa) of three models configurations under lateral bending (left) and axial rotation (left). **PED:** Pedicle screw; **ROD:** rod.

In extension, the minimum stresses for the L4 pedicle screw were found with the bilateral model. With respect to the bilateral model, an increase of 37 MPa was found for the unilateral model. For the oblique model, an increase of the stresses was observed with respect to the bilateral model, but a decrease with respect to the unilateral model up to 20 MPa (Figure 3).

In flexion, results similar to the extension case were found, but with a lower difference between the unilateral and the oblique models; the highest difference was found between the bilateral and the unilateral models (41 MPa) (Figure 3).

For lateral bending, similar stresses were predicted among the three instrumented models; the maximal difference was 6 MPa between the bilateral and the unilateral models (Figure 4).

For axial rotation, negligible differences were found between the bilateral and the oblique models. Instead, the unilateral model showed a significant increase compared with the other two models, with higher stresses up to 35 MPa (Figure 4).

Stresses in the L5 Pedicle Screws

As for the stresses for the L4 pedicle screws, only the stresses for lateral bending and axial rotation on the left side were reported.

In extension, the minimum stresses in the L5 pedicle screws were found with the bilateral model. Regarding the latter model, an increase of 60 MPa for the left screw was found for the unilateral model. For the oblique model, an increase of 93 MPa for the right screw was observed with respect to the bilateral model (Figure 3). In flexion, results similar to the extension case were found (Figure 3). For lateral bending, the stresses in the left screw resulted higher for the unilateral model with respect to the bilateral model. For the right screw, instead, stresses resulted higher for the bilateral model (40 MPa) with respect to the oblique model (37 MPa) (Figure 4).

In axial rotation, results similar to lateral bending were found only for the left screw. On the right side, for the oblique model, an increase of 15 MPa was observed with respect to the bilateral model (Figure 4).

Overall, the highest values of stresses in the L5 pedicle screws on both sides of the vertebra were observed with the oblique model in extension and flexion and with the unilateral model in lateral bending and axial rotation (Figure 3, Figure 4).

Stresses in the Posterior Rods

As for the stresses for the L4 and L5 pedicle screws, only the stresses for lateral bending and axial rotation on the left side were reported.

In extension, flexion, lateral bending, and axial rotation the maximum stresses on the left rod were higher for the unilateral model with respect to the bilateral model. A maximal difference of 26 MPa between these two models was found in flexion (Figure 3, Figure 4).

Overall, the highest stress values for the rods were observed for the oblique model in extension, flexion, and axial rotation and for the unilateral model in lateral bending. However, a maximal difference of 115 MPa was found between the bilateral and the oblique model in extension.

DISCUSSION

A wide range of posterior instrumentations, combined with interbody cages, has been proposed to provide an efficient and stable mechanical environment that promotes bony fusion. In the last decades, biomechanical studies have shown bilateral pedicle screws represent the most common and stable construct and can be considered the gold standard. Although with the limitation of a pure finite elements study, our research demonstrates similar results.

Unilateral pedicle screws with or without the adjunct of translaminar screws have shown satisfactory clinical outcomes with less surgical time, less blood loss, and lower cost (8,12,20). Despite this, the bilateral pedicle screws are the most stable fixation, providing the highest ROM limitation and less mechanical stress on screws and rods. In flexion and extension, unilateral and oblique fixation showed similar results as far as the mechanical stresses for the screws (125 MPa or more). In lateral bending and axial rotation, the unilateral fixation determined higher stresses on the screws compared to the oblique modality. Oblique fixation is characterized by the highest stresses for the rod in flexion, extension and axial rotation, probably due to the level arm caused by a longer rod. In this modality, the highest value was reported in extension (more than 125 MPa), while the stresses in axial rotation and lateral bending were significantly lower (less than 50 MPa).

Literature reports about implant failures vary because of significant heterogeneity in a population study, diagnosis, and type of surgery (5,6,15,22). A study by Mohi Eldin et al. reported screw breakage as the most common cause of mechanical failure followed by rod breakage (14). However, this study was based on a heterogeneous population and included short and long fusions for post-traumatic instability. However, mono-segmental anterior and posterior fixation has proven to be stable constructs with a high percentage of fusion (14). In this scenario, with a large bi-cortical cage that lays on the endplate apophyseal ring providing significant stability, it seems that the posterior instrumentation is less stressed, and alternative ways of fixation, rather than bilateral pedicle screws, are feasible.

Our results are comparable to other reports already present in the literature. The oblique and unilateral comparison showed similar mechanical stress scores on the screws, but the oblique modality is associated with higher stress on the rod. This last result is probably due to a longer rod and an increased level arm. We do not have enough data to foresee the consequences of this higher stress on the rod in the oblique fixation. Still, more rigorous and exhaustive clinical studies are necessary to confirm the present knowledge on this topic. In general, the higher risk of instrumentation failure in mono-segmental lumbar fusion is screw breakage rather than rod failure, as suggested by Mohi Eldin et al. (14). For this reason, although our study is a pure finite element analysis, it seems that the oblique fixation associated with an anterior interbody fusion could have a possible clinical implication in the near future, considering the advantages of less time and fewer risks, less blood loss and fewer costs. Of course, despite these results, further studies will be necessary to test this technique's clinical feasibility.

As in several in vitro and computational studies (7,23), in this study, only pure bending moments were used as loading conditions for the spine; a compressive load representing the body weight, such for example a follower load (17), has not been used in combination with these moments. Although this can be seen as a limitation of the present study, using only pure moments has been recognized as a good method to simulate realistic loading conditions when testing spinal implants (24). Another limitation concerns the tie constraints used for modelling the bone-implant interaction, which does not allow for relative motion and therefore simulates a perfect osteointegration which may not always be achieved in clinical practice.

Most importantly, two further limitations should be underlined. On the one hand, the FE model does not integrate the strength of the ligamentous structures. In particular, the supraspinous ligament performs essential functions of stability. It follows that this substantially limits the quality of the model's results. On the other hand, in a possible clinical application, the rod placement could injure the supraspinatus ligament and further weaken the tension capacity of the ligaments. In particular, this last aspect could significantly compromise any clinical application if not solved with engineering or design rod solutions.

CONCLUSION

The results of our study confirmed the significantly higher stress levels for the rod and pedicle screws in cases of oblique or unilateral configuration systems if compared to the standard bilateral one. In particular, the oblique configuration has stress properties comparable to the unilateral in terms of axial rotation.

In conclusion, the unilateral or oblique instrumentation configuration can be considered an option only in cases with good bone quality and an interbody cage with good bi-cortical support. The finished model-tested results require further investigations to consolidate the knowledge acquired before evaluating the clinical applicability.

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Competing interests: M.D. and R.C. are consultants for Nuvasive – Medacta; D.V. is consultant for Styker.

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AUTHORSHIP CONTRIBUTION

Study conception and design: AR, FL, DV, FG
Data collection: AR, FL, DV, MPo, RC
Analysis and interpretation of results: AR, FL, DV, MPa, FG, MD
Draft manuscript preparation: AR, FL, DV, MPa, MD
Critical revision of the article: AR, FL, DV, MPo, RC
Other (study supervision, fundings, materials, etc...): FG
All authors (AR, MPa, RC, MD, DV, MPo, FG, FL) reviewed the results and approved the final version of the manuscript.

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