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Limiting interpedicular screw displacement increases shear forces in screws: A finite element study

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A B S T R A C T

Background context: Screw loosening has been reported for non-fusion devices. Forces on pedicle screws could be related to kinematic parameters as the interpedicular displacement (ID), which consists of the displacement between superior and inferior screw heads from full extension to full flexion.

Purpose: To investigate the relationship between ID and screw loosening for different designs of posterior implants using a finite element model.

Methods: An L3-sacrum previously validated spine FE model was used. Three-rod designs were considered in L4-L5 segment: a rigid screw-rod implant, a flexible one and a specific design with a sliding rod providing limited restraint in ID. In order to simulate intermediate configurations, the friction coefficient between the sliding rods and connectors were varied. The sacrum was rigidly fixed. Rotations (flexion-extension, lateral bending and axial rotation) were applied to L3, for each modeled configuration: intact, injured, injured with different implants. Model consistency was checked with existing experimental in vitro data on intact and instrumented segments. Screw loads were computed as well as ID.

Results: In flexion-extension, the ID was less than 2 mm for rigid (R) and flexible (F) constructs and 5.5 mm for intact spine and the sliding implant (S3). Screw's shear forces were 272 N, 153 N, 43 N respectively for R, F and S3 constructs.

Conclusions: Implants that allow ID presented lower screws loads. A compromise between the ability of the implant to withstand compressive forces, which requires longitudinal stiffness, and its ability to allow ID could be important for future implant designs in order to prevent screw loosening.

Keywords:

Lumbar spine biomechanics
Facet supplementation
Segmental kinematics
Annulus stress
Adjacent levels

1. Introduction

In severe stages of discopathy, osteoarthritis, degenerative spondylolisthesis and spinal stenosis, surgical treatment may be indicated after unsuccessful conservative treatment. Posterior spinal fusion and eventually spinal canal decompression represent traditional surgical techniques. Pedicle screw fixation is present in many of posterior instrumentations systems. Rods and blockers link the screws and a cross-link between right and left rods may be used to enhance stability in axial rotation. These devices are commonly used to stabilize the spine and to obtain fusion of bone graft between the instrumented vertebrae. Although widely used,

mechanical adverse effects, such as adjacent segment degeneration (ASD), may occur following rigid instrumentation and fusion [1].

With that issue in mind, motion-preserving devices were advocated [2]. Within these types of implant, posterior pedicle screws were connected by various types of rods, such as flexible rods or tension bands surrounded by flexible spacers, others designs may include a sliding between the screws and the rods [3]. Those motion-preserving devices aim to reduce motion at the instrumented segment without suppressing it, thus limiting stresses transmitted to adjacent segments. To date, clinical results for dynamic implants are variable, with studies reporting between 0% and 72% rates of screw loosening in non-fusion instrumentation [4].

The screw loosening may be related to shear and normal internal stresses in the bone surrounding screws. These stresses relate to generalized forces in the screws because of action-reaction principle and such forces could depend on the implant design.

Although in vitro methods were proposed to obtain forces in screws [5–7], these require adaptations in pedicle screws, making it difficult to measure internal forces in clinical studies. New

Table 1
Material properties and formulation for the lumbar spine model.

Structure	Material formulation	Elastic modulus (MPa)	Poisson ratio	Reference
Cortical bone on vertebral body	Linear isotropic	12,000	0.3	[18]
Cancellous bone		100	0.3	[18]
Posterior bony elements		3500	0.3	
Cartilaginous endplate		24	0.4	[28]
Annulus fibers	Tension-only linear	Changes according to circumferential and radial position on the intervertebral disc		[29]
Annulus matrix	Multilinear isotropic	Multilinear	0.45	
Nucleus	Linear isotropic	1	0.499	[28]

parameters were investigated in order to evaluate dynamic implants such as interpedicular displacement (ID) [8], which consist of the displacement of screws heads (superior and inferior screws from one side) between full extension to full flexion. This parameter (ID) could be related with forces in screws. This ID parameter could be accessed in clinical studies using dynamic radiographs [9]. Our hypothesis is that there could be a relationship between ID and screw forces. Such finding could help to understand the screw-loosening phenomenon.

Internal stresses on screws can be estimated using finite element (FE) models [10]. Several previous FE studies were performed to compare the mechanical behavior of different spinal implant concepts [11–15]. However, no FE study has investigated the relation between loads in screws and the ID parameter.

The purpose of this work is to investigate the relationship between ID and screw loads. Intervertebral disc stress will also be investigated. A FE model is used to analyze different design concepts, which have a wide range of ID:

- sliding articulated;
- flexible;
- rigid (fusion).

2. Material and methods

2.1. Finite element model

A previously validated L3-S1 spinal FE model was used [16–19]. Eight-node hexahedral elements were used to model cancellous and cortical bone, vertebral end-plates, nucleus pulposus and annulus fibrosus ground substance. The composite nature of the intervertebral disc was modeled by embedding the annulus matrix with fibers represented by 2-node traction-only cable elements. All ligaments were modeled by cable elements and facet joints were modeled using surface contact elements (Table 1).

The injured configuration represented a surgical decompression (bilateral facetectomy and laminectomy) that was simulated by removing elements from the posterior arch. Supraspinal, interspinal and flavum ligaments between L3-L4 and L4-L5 were also removed.

Different configurations were studied:

- intact spine;
- non-instrumented injured spine;
- instrumented injured spine with three different kinds of rods (Fig. 1).

The instrumentations were placed at the L4-L5 motion segment. The four screws were modeled using beam elements. The same screws positioning and modeling were used for all the three different configurations, as in a previous numerical study [16].

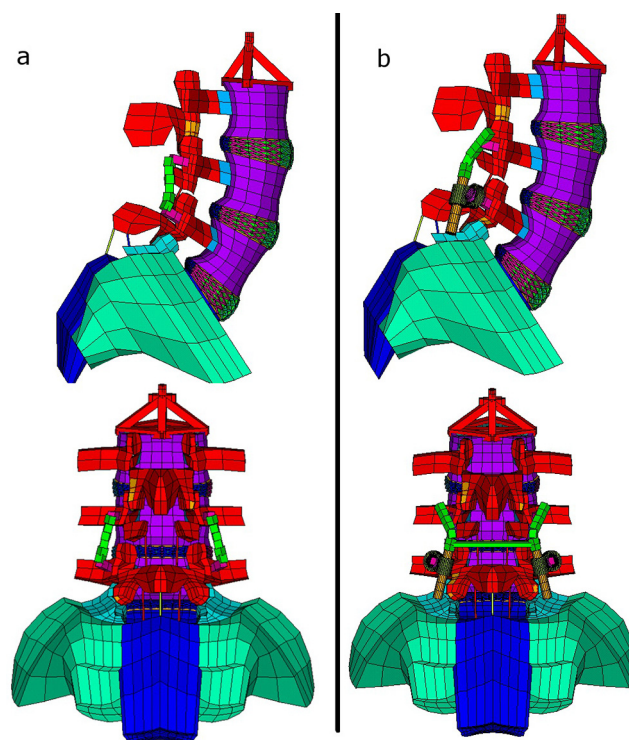


Fig. 1. Instrumented finite element model of a L3-sacrum vertebral segment: lesion + flexible or rigid implant; b: lesion + sliding implant.

The rigid implant (R) was modeled using beam elements with Young modulus of cobalt- chromium-molybdenum alloy ($E=241$ GPa). The flexible implant (F) was modeled by reducing the Young modulus of the rods ($E=241$ MPa) to match the axial stiffness of flexible implants as referenced in the literature (200 N/mm) [20]. Thus, the reduced Young's modulus of the flexible rod was 1000 times lower than the Young's modulus of the rigid rod.

In order to simulate the extreme case where the ID has no restraint and intermediate configurations, a sliding implant was used. The sliding implant was modeled as described in a previous work [16]. Simulations were performed in flexion-extension, the friction coefficient between the sliding rods and connectors was varied in order to increase longitudinal stiffness and evaluate the relation between the resulting ID and loads in screws. Values used for this friction coefficient were 0 (S1), 0.05 (S2), 0.1 (S3), 0.2 (S4), 0.3 (S5), 0.4 (S6) and 1 (S7).

Validation of the instrumented spine with the sliding rod model was performed by comparing its range of motion (ROM) behavior with respect to six cadaveric specimens previously tested in vitro [3]. Consistency of the rigid construct modeling was also checked with regard to existing in vitro data on 8 specimens.

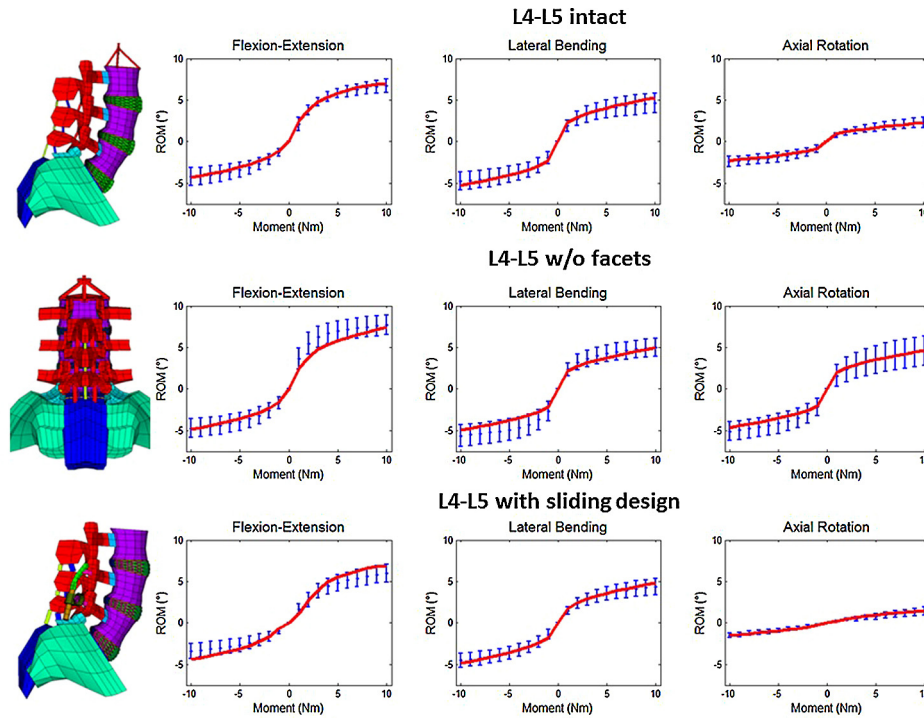


Fig. 2. Model validation: range of motion for different configurations. The experimental corridor consists of the mean of 6 cadaver specimens with the confidence interval of two standard deviation of measures.

The sacrum was rigidly fixed. A compressive follower load of 400 N was simulated as described by Renner et al. [21]. Prescribed rotations for different directions were applied to the cranial vertebra L3: 17° in flexion, 14° in extension, 13° in right lateral bending and 9° in left axial rotation, as described in a previous numerical investigation [16].

Normal and shear forces for beam elements representing the screws were obtained as well as the Interpedicular Displacement (ID) [8]. Von Mises stress was also computed for the instrumented (L4-L5) and adjacent segments (L3-L4 and L5-sacrum).

3. Results

3.1. Model validation

The FE model L4-L5 ROM was within the range of the in vitro experimental data for intact, facetectomy and instrumented (sliding rod) configurations (Fig. 2). A friction coefficient between rod-connector was assumed as 0.1 for validation purposes (S3 configuration). This value was obtained using a parameter identification approach, comparing computational results to experimental data in flexion loading.

3.2. Screws forces and interpedicular displacement

Interpedicular displacement varied between 0 for the R configuration and 6.5 mm for the S1 configuration (Fig. 3).

Right and left screw forces results were identical in this model. Results will be presented as maximum value at each node of the right screw. Positive normal forces were defined in the pullout direction of the screw.

The interpedicular displacement was compared to the maximal shear force (Fig. 4) and normal forces (Fig. 5) in screws for flexion-extension loading. Rigid implant presented the highest shear force (272 N), sliding implant presented higher shear forces than flexible only when friction coefficient was equal or higher than 0.4.

A relationship between the interpedicular displacement and maximum shear force was observed. For normal force the same relationship was not observed.

3.3. Annulus Von Mises stress

Similar trends were found in flexion, extension and lateral bending. Peak values in the instrumented level increased with a higher interpedicular displacement, while the opposite tendency was found for adjacent levels. Results for extension loading are presented as example (Fig. 6).

In axial rotation, sliding and rigid implants increased Von Mises stress in inferior adjacent level (peak: 1.33 MPa), while the stress in adjacent levels with the flexible rod was comparable to the injured configuration (peak: 0.89 MPa).

4. Discussion

From a clinical point of view, various types of posterior dynamic instrumentations may be considered for different indications in the lumbar spine. This type of devices is intended to reduce the risk of adjacent segment degeneration. However, their clinical significance remains controversial, as the long-term effect on adjacent lumbar segments has not been proven clinically to date [4]. Furthermore, the implant's design and capacity to restore segmental lordosis appear crucial, as a lack of lordosis within the instrumented segments might induce a compensatory risk of adjacent hyper-lordosis and thus increase the risk for facet joint deterioration [22]. These different designs can yield different ID, which could be related with loosening issues. This work used a spinal finite element (FE) model with the aim of understanding the relationship between a kinematic parameter that varies with the implant design, the ID, and the internal loads on implants and intervertebral discs.

As any spinal FE model, there are limitations since muscles and gravitational loads are not represented. Moreover, it is difficult to validate all the results, particularly when considering internal

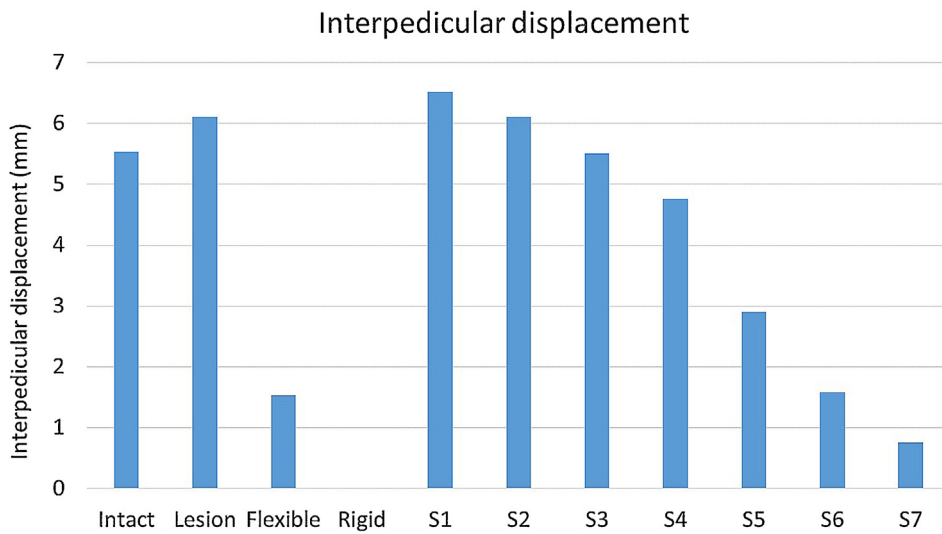


Fig. 3. ID for different configurations.

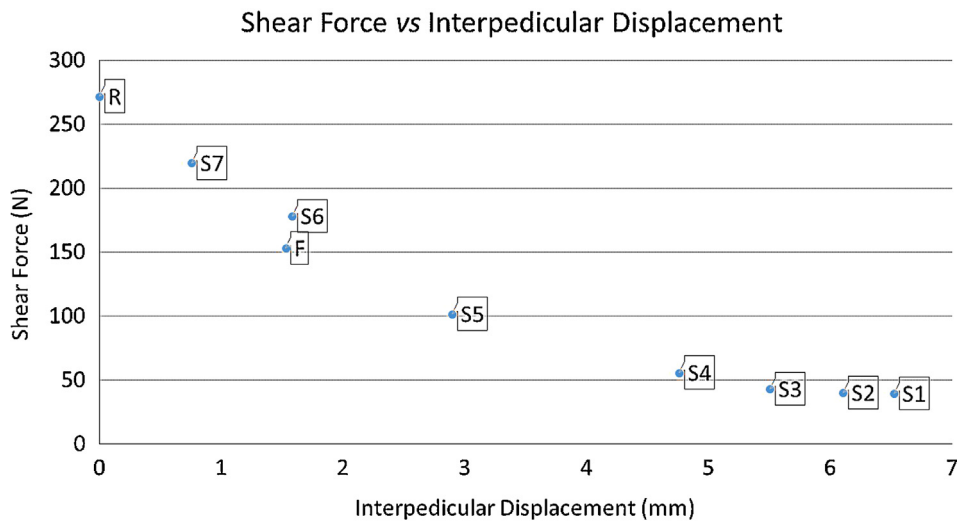


Fig. 4. Relationship between ID and maximum shear forces in screws. R-rigid implant; F-flexible implant; S-sliding implants with different frictions coefficients (S1 to S7).

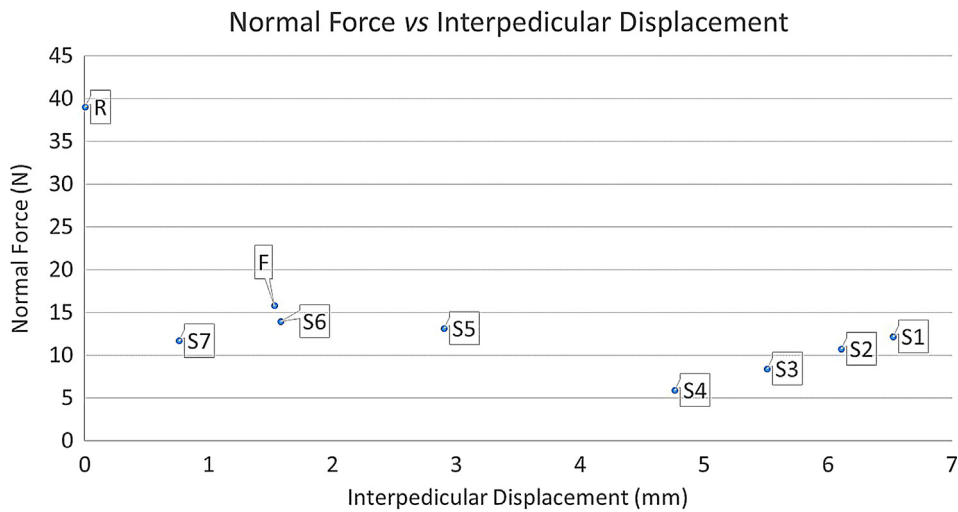


Fig. 5. Relationship between ID and maximum normal forces in screws. R-rigid implant; F-flexible implant; S-sliding implants with different frictions coefficients (S1 to S7).

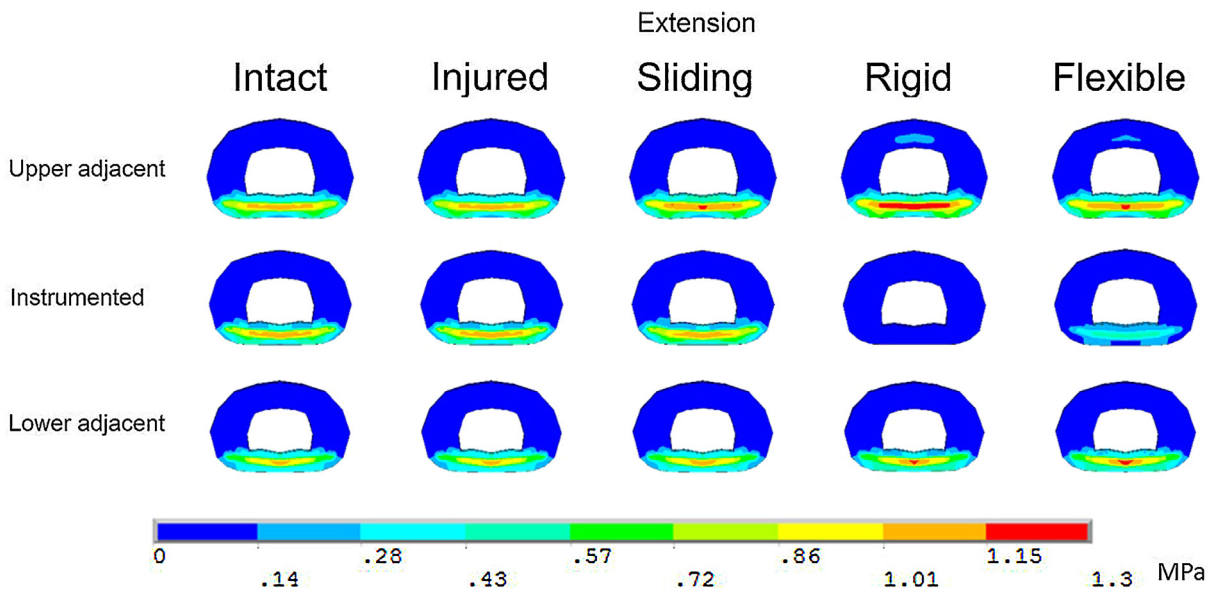


Fig. 6. Von Mises stress of the intervertebral disc in extension loading. Results are presented as an axial middle cut in the intervertebral disc.

forces or stresses. However, the global consistency of the model was checked using in vitro data, in which the mobility curve of the model was compared with an experimental corridor in different configurations. The model is within the experimental corridors except for the initial part of the curve, in the configuration without facets. Even in this case, the difference is lower than 0.5° .

Validating finite element models of intervertebral discs in relation to the stress distribution in models is not an easy task because it would require pressure measurements which distribution could be variable within the disc space. This limitation, which is inherent to such numerical studies, should be kept in mind. However, FE models present the advantage of having their geometry and material properties controllable, in such they are useful for comparative biomechanical studies, with the aim to clarify the main factors related to instrumented spine biomechanics.

Different conceptual implants resulted in different IDs that were compared to normal and shear forces in pedicle screws. Normal force relates to classic pullout tests, which are widely used to evaluate the strength of screw-bone assembly [23,24]. Even though those tests are used to evaluate the grip of a screw, screw loosening could also be related to shear forces between screw and bone interface. Shear forces might progressively loosen the bone around the screw during daily physical activities [25]. This phenomenon of toggle migration could drastically decrease the pullout strength, weakening the desired fixation [26]. The results in the present study showed that when an implant design allows ID, shear forces are reduced in the screws.

Implant design and associated IDs showed to be also related with intervertebral disc Von Mises stress. In the present study, it was demonstrated that allowing ID would decrease stress in adjacent discs, whereas limiting ID would decrease stress at the instrumented segment. These considerations are clinically relevant when deciding on the amount of stabilization required at the instrumented level versus risk of adjacent segment degeneration and screw loosening.

Yeager et al. [27] compared the ID of different implants using in vitro experiments. In their results, no significant differences were observed between the IDs of rigid and flexible designs for flexion-extension. Even if the protocols are not strictly comparable, comparing their results with ours, the ID found with the FE modeling was in the experimental range for intact, lesion and with flexible implants. A difference was found when comparing IDs for the rigid

implant configuration (FE model = 0; in vitro = 2.44 ± 1.15 mm). The higher in vitro ID could be related to a sliding between the screw and rod, which were not taken into account in our modeling of rigid implant. Further experimental studies on ID with thorough observation of local phenomenon could help understanding this issue.

Nevertheless, to our knowledge, this is the first work that obtains the ID in finite element modeling and the result highlights the relation of limiting ID and stresses in screws or intervertebral discs. ID can be an important factor to be taken into account in future implant designs, when screw loosening issues are concerning. In clinical practice, with a given implant, ID may be variable among individuals and with time. Future studies considering in vivo ID measurements could help to understand possible changes in ID related to clinical outcome.

Disclosure of interest

L.V.P.C.L., P.R. and W.S. declare that they have no competing interest.

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