D. S. Fidaldo et al., A minimally invasive anterior lumbar interbody fusion at the L5-S1 level, Revista Mecânica Experimental, Nº 33, APAET (2021), pp.51-57.

A minimally invasive anterior lumbar interbody fusion at the L5-S1 level

Resposta cinemática da unidade funcional L5-S1 após fusão intervertebral lombar recorrendo à abordagem lateral

D. S. Fidalgo[1] | **B. Areias**[2] | **L. C. Sousa**[2(*)] | **M. Parente**[2] | **R. Natal**[2] | **H. Sousa**[3] | **J. M. Gonçalves**[4]

[1]MIEM, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal, Portugal
[2]INEGI e DEMec, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal
[3]Centro Hospitalar de Vila Nova de Gaia / Espinho, Vila Nova de Gaia, Portugal
[4]Faculdade de Medicina da Universidade do Porto, Hospital da Luz Arrábida, Porto, Portugal
[(*)]*Email:* lcsousa@fe.up.pt

abstract

Lumbar spinal fusion has evolved as a treatment option for symptomatic spinal instability, spinal stenosis, spondylolisthesis, and degenerative scoliosis. This work presents a minimally invasive anterior lumbar interbody fusion (ALIF) at the L5-S1 level, applying the SynFix implant in order to investigate spine stability during the recovery considering the early and long-term postoperative phases. In the early postoperative phase, namely for extension load case, rotation angles are much greater than the ones obtained in the long-term postoperative phase, showing a greater spine instability.

Keywords: Finite element method, SynFix, minimally invasive lumbar fusion, anterior lumbar interbody fusion.

resumo

A fusão intervertebral é uma técnica cirúrgica cada vez mais utilizada no tratamento da instabilidade sintomática da coluna vertebral, nomeadamente a estenose espinhal, a espondilolistese e a escoliose degenerativa. Este trabalho apresenta uma fusão intervertebral anterior minimamente invasiva (ALIF) no nível L5-S1, aplicando o implante SynFix para investigar a estabilidade da coluna durante a recuperação, considerando a fase inicial e a fase final do pós-operatório. Na fase inicial, principalmente no caso de carga de extensão, os ângulos de rotação são muito maiores do que os obtidos na fase final do pós-operatório, evidenciando maior instabilidade da coluna vertebral.

Palavras-chave:

1- INTRODUCTION

Spinal Fusion is a surgery used to relieve the pain in cases of severe instability of the spine, when the vertebrate bodies start to slip, causing chronic back pain and symptoms of nerve compression. This technique will not interfere with the patient's mobility or flexibility, particularly because the patient does already suffer reduced mobility from the symptoms. Nowadays surgeons use minimally invasive techniques as an alternative to open spine surgery. A smaller incision reduces damage to surrounding tissue, blood loss and scarring. In addition, this reduction in tissue trauma yields better pain outcomes and fewer infections, which results in a faster recovery time and less hospital stay [1,2]. The linking of vertebrate bodies creates an additional mechanical strain on the adjacent segments of the spine and consequently has the potential to increase spinal disc degeneration and discomfort.

Spinal fusion surgery simulations allow the knowledge of the lumbar spine kinematics, the development of new spinal implants and the optimization of surgical interventions.

Surgeons usually prefer ALIF, when the patient suffers from spondylolisthesis, abnormal spinal curvatures such as scoliosis or kyphosis, degenerate disks or spine instability. The main advantage associated with ALIF is the prevention of damage to posterior structures, as the posterior ligaments and posterior muscles are preserved [3]. Furthermore the possibility of disk space expansion and indirect decompression, are also considered when choosing the approach. However, the possibility of damaging the nerves, abdomen organs or large blood vessels, persistent pain after the surgery, and removal of the anterior longitudinal ligaments, are some disadvantages [4].

The SynFix implant System is a stand-alone anterior interbody fusion device indicated for use in patients with degenerative disc disease at one or two contiguous levels, from L2 to S1. The main goal of this work is to investigate spine stability after an ALIF approach using a specific implant, the SynFix implant (Fig. 1). For this purpose, the spine biomechanical behaviour in the early and long-term postoperative phases is compared. This study can help surgeons choosing the best option for a lumbosacral dysfunction treatment.

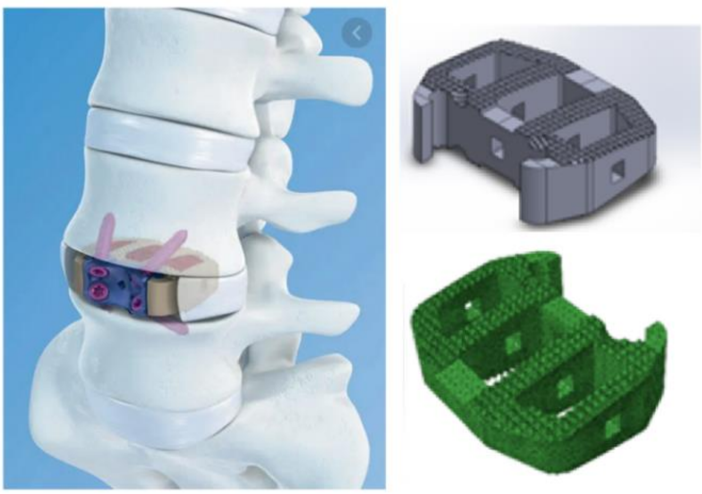

Fig. 1 | Interbody fusion using the direct anterior approach and the SynFix implant.

2- METHODS

In order to simulate the mechanical behaviour of the spine segment, a finite element model of the L5-S1 functional spinal unit (FSU) was created using computer tomography images. The definition of the intervertebral discs of the L5-S1 functional spine unit was performed using commercial software Mimics (version 10.0, Materialise Inc., Belgium) and Abaqus/Cae (2007). Due to its lower density, the intervertebral discs are not visible in a CT. The geometry of the intervertebral disc was defined using the lower surface of L5 and the upper surface of S1. A plane was defined slightly above the lower surface of L5 and the disc geometry was obtained, by extruding the elliptical sketch in direction to S1, and extending slightly below the superior endplate of S1. The disc was partitioned into two regions, the inner nucleus pulposus and the peripheral annulus fibrosus taking into account the volumetric ratio 3:7, respectively. The annulus is a viscous substance reinforced by a crisscrossing network of collagen fibres. The orientation alternates from layer to layer, oriented at an angle of ± 30° with respect to the horizontal plane.

All ligaments, anterior and posterior longitudinal ligaments (ALL and PLL), intertransverse (ITL), interspinous (ISL), supraspinous (SSL), flavum (LF) and capsular (CL) ligaments, and intervertebral joint layers were modelled: tension-only spring connector elements, truss elements T3D2, were used to mesh ligaments and eight-noded hexahedral elements with a hybrid formulation C3D8H for joint layers.

After the definition of L5-S1 FSU the chosen implant, manufactured with a biocompatible polymer, was inserted. The SynFix cage [5], occupies almost the entire area of the intervertebral disk. The implant geometry is characterized by 38 mm length, 30 mm width, 13.5 mm height and a lordotic angulation equal to 12º. 38488 nodes and 169153 four node tetrahedral elements, C3D4, were used to mesh the implant. In order to allow implant insertion via anterior approach, the anterior longitudinal ligaments and the nucleus pulposus were removed, and only 1/3 of the annulus fibrosus was preserved.

The implant central windows were filled with autogenous bone graft to promote intervertebral fusion and then the implant was placed in the central area of the intervertebral space. Figure 2 shows the L5-S1 FSU model with the SynFix implant. The implant must be applied with anterior supplemental fixation according to technical specifications: four pedicle screws and a fixation plate [5]. The screws and the fixation plate disposition are also illustrated in Figure 2. Each screw and the fixation plate were meshed with four node tetrahedral elements C3D4. 2245 nodes and 8888 elements were used to mesh each screw. The fixation plate was meshed with 1825 nodes and 7005 elements.

3- LOADS AND BOUNDARY CONDITIONS

In order to apply the loads a point load was applied to a reference point in the center of the superior surface of L5, which was connected to all the nodes of the superior endplate surface by kinematic

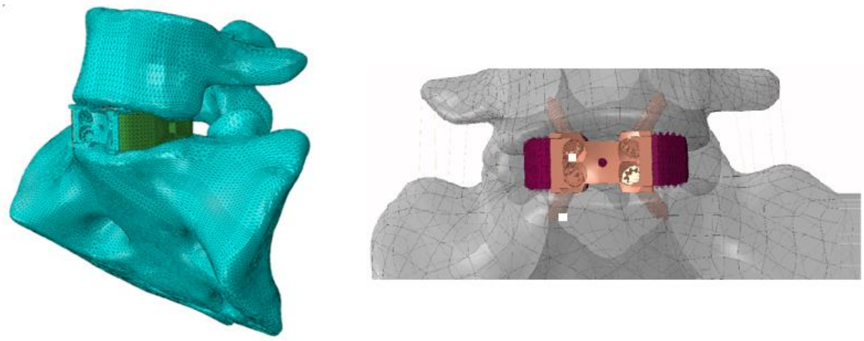

Fig. 2 | L4-L5 functional unit: vertebrae and oracle cage finite element mesh and supplemental fixation.

coupling. Then the created model was subjected to loads corresponding to daily activities: a compression force of 150 N and pure moments of 10 Nm were applied to the reference point.

All nodes of the inferior end plate of the S1 vertebra were constrained from moving in any direction.

4- CONTACT CONDITIONS AND MECHANICAL PROPERTIES

In this study, two postoperative phases were considered, an early and a long-term postoperative phase, modelled with different contact conditions type. In the first postoperative phase, the intervertebral fusion has not yet occurred, and a "surface to surface" contact interaction between the vertebral endplates and the autogenous graft bone/SynFix cage was applied, as this constraint allows relative motion between the involved surfaces. On the other hand, to simulate the long-term postoperative phase, a "tie" constraint was applied, in order to define de contact between these surfaces. This contact condition ties two separate surfaces together with no relative motion between them.

All components were modelled considering elastic behaviour [6-7], except for the annulus fibrosus and the nucleus pulposus, whose fibres were considered an anisotropic hyperelastic material and modelled according to the Holzapfel constitutive model [7]. The nucleus pulposus behaviour, was characterized by a hyperelastic formulation, the Neo-Hookean model [6], with C_{10} = 0.16 MPa D = 0.024 MPa. The implant is manufactured with a biocompatible polymer (PEEK). All the properties are shown in table 1.

5- RESULTS AND DISCUSSION

The FSU model was solved using Abaqus Explicit. Fig. 3 shows axial displacement field for the extension and torsion load cases. As expected, in the early postoperative phase, axial displacement values are always greater than the ones observed in the long-term postoperative phase,

Table 1 | Mechanical Properties.

Ligaments	Young Modulus E [MPa]	Poisson Ratio *v*	Section Area [mm^2]	Number of Elements
Anterior Longitudinal ALL	20	0,3	8	5
Posterior Longitudinal PLL	70	0,3	4	5
Intertransverse ITL	28	0,3	2,5	4
Interspinous ISL	20	0,3	6,7	6
Supraspinous SSL	28	0,3	3	3
Flavum LF	50	0,3	13,3	3
Capsular Ligament CL	50	0,3	5	6
Vertebrae Cortical bone	1200	0.3		
Vertebrae Trabecular bone	100	0,2		
Sinfix (Peek)	3500	0,3		
Screws and bars	105000	0,34		
autogenous iliac bone	1500	0,3		

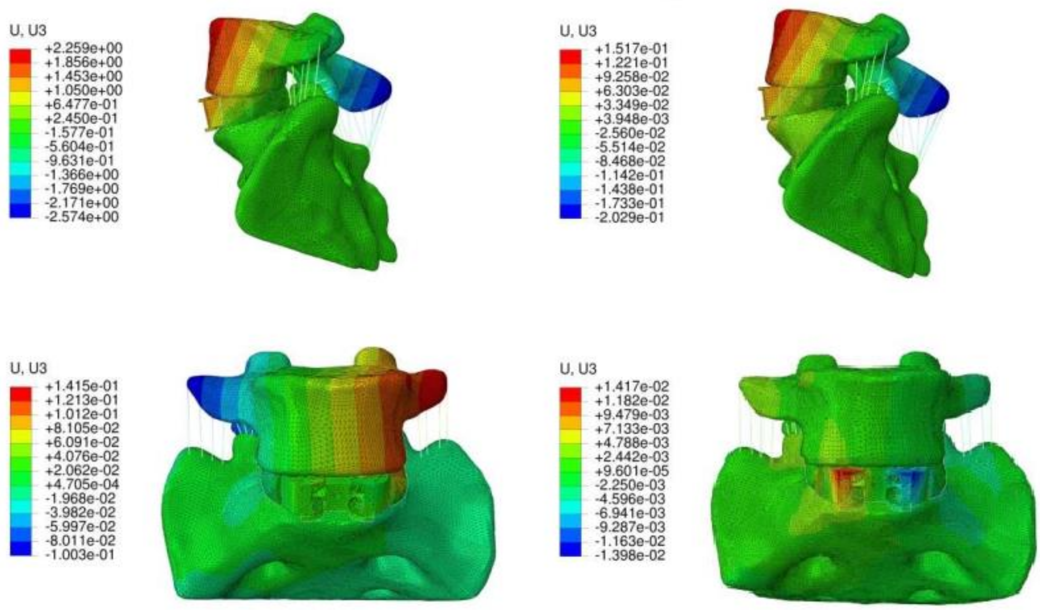

Fig. 3| Displacement field for extension (top) and rotation (bottom) load cases: early (left) and long-term (right) postoperative phases.

as fusion has not yet occurred. In the two postoperative phases, the highest maximum displacement is associated with the extension load case and the smaller with torsion load case. The large area of SynFix cage leads to a lower displacement value, during rotation load case, even during the early postoperative phase.

Fig. 4 presents maximum rotation angles for all load cases and for the two postoperative phases. Once again, lower rotation angle values are found in both postoperative phases. A greater discrepancy between the two phases is found in the extension load case probably due to the large area of the implant. Rotation angle discrepancies between the load cases are greater in the early postoperative phase, during which fusion has not yet occurred. In the early postoperative phase the highest rotation angle is found in the extension load case. Lateral bending and rotation load cases present the smallest rotation angle due to the large implant area. In the long-term postoperative phase extension and flexion present similar rotation angles as fusion has already happened. Once again lateral bending and rotation load cases present the smallest rotation angle.

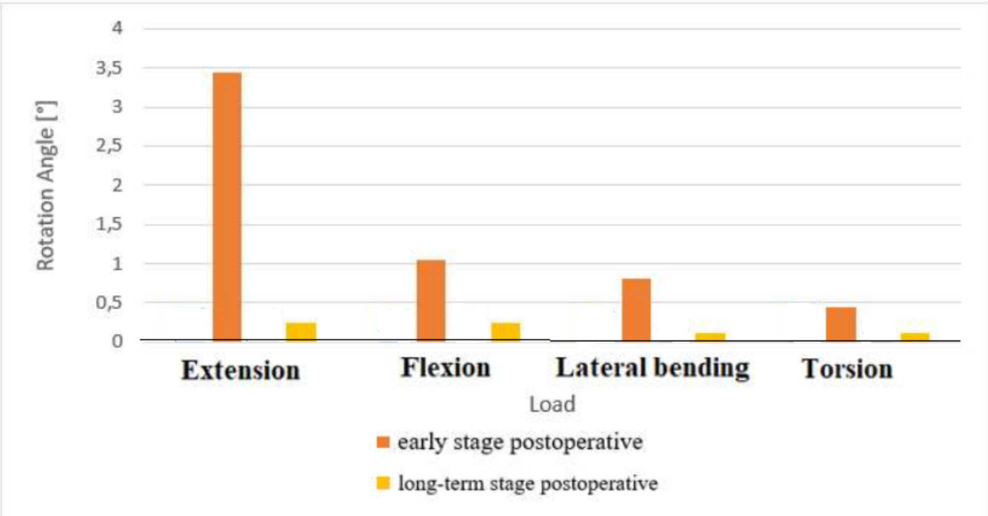

Fig. 4| Rotation angle comparison between early and long-term postoperative stages.

6- CONCLUSIONS

Numerical simulations of lumbar interbody spine fusion present low costs and no risks to the biological tissue (bone).

Results show that the early recovery phase is less stable than the long-term postoperative phase, as greater rotation angles and axial displacements are found in the first postoperative phase. These findings meet expectations, as in the early postoperative phase, fusion bone mass is not yet established.

This study shows that numerical simulations of lumbar interbody spine fusion may be useful to optimize implants and surgeries.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the funding by FCT, Portugal, the Research Unit of LAETA-INEGI, Engineering Faculty of University of Porto.

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