Investigation of the stability of two different spondylolysis surgical techniques utilizing finite element simulation

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Abstract

Spondylolysis is defined as a unilateral or bilateral bony defect in the pars interarticularis or isthmus of the vertebra. It is most commonly observed affecting the lumbar vertebrae, manifesting as a fracture that results in low back pain and poor quality of life of the patient. Spondylolysis is frequently treated by spinal fusion, a common surgical procedure, but it can result in a loss of motion at the fused level and potentially increase loading on adjacent segments. As an alternative solution, Gillet introduced a V-shaped rod that demonstrated greater advantages in comparison to the spinal fusion technique. In the context of the aforementioned topic, our previous results highlighted the significance of the lubricity effect of human materials present in the surgical area (blood, fat), which has the potential to markedly reduce the friction coefficient between the spinal rod and the locking screw.

The objective of this study was to compare the fracture stability of the two different systems, with and without consideration of the effects of the lubricity of human materials. The spinal fusion and V-rod systems were investigated in Ansys v19 with L1-L4 vertebrae and discs. A fracture was formed on the L2 vertebra and different loads were applied to measure the difference in stability. The simulations were conducted in dry and lubricated conditions.

The results demonstrated no significant difference between the two stabilizing methods, but the importance of lubrication effect of human materials was established.

Keywords: spondylolysis, spine, biomechanics, finite element analysis, friction

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Introduction

Spondylolysis is a condition characterised by a defect or stress fracture in the pars interarticularis, typically in the lower lumbar spine (L4 or L5, *Figure 1*). Individuals afflicted with spondylolysis frequently experience low back pain, which may radiate into the buttocks or thighs, and which usually worsens with physical activity and improves with rest. The pain is particularly noticeable during extension or rotation of the spine. The condition is often caused by overuse or repetitive strain of the lower back, which is common in athletes. Genetic factors or congenital defects can also contribute to the development of spondylolysis, and trauma or injury to the spine can also be a causative factor. Treatment for spondylolysis usually involves rest and activity modification to reduce stress on the spine. Physiotherapy is often recommended to strengthen the muscles that support the spine, and painkillers can help manage symptoms. In severe cases, surgical intervention may be considered to repair the defect or stabilize the affected vertebra. Several surgical solutions are applied, such as cable-screw[1], wire[2] and hook-based.[3] However, spinal fusion is the most commonly used approach.

Spinal fusion is a surgical procedure that provides stability by permanently fusing two vertebrae together, thereby preventing any movement between them. This procedure is often recommended for elderly patients suffering from painful spondylolysis or for those with adjacent discs showing signs of degeneration. In this procedure, a bone graft is usually placed between two vertebrae to promote the process of fusion. Over time, new bone growth replaces the graft, which acts as a scaffold. The surgeon may also use metal screws and rods to hold the vertebrae in place as they heal and fuse.[4]

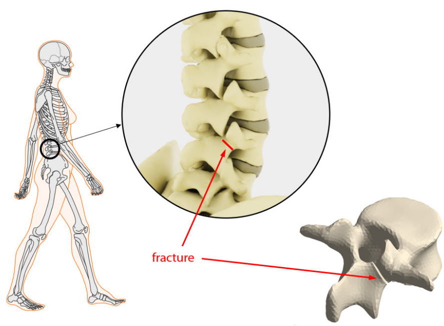

Figure 1. Anatomical location and structural representation of spondylolysis

At the Wuzhou Red Cross Hospital (Guangxi, China), another alternative surgical method called the V-rod technique is being used in surgery for spondylolisthesis.[5] During the surgery, a pair of screws are inserted at the pedicles of the affected vertebrae and the unstable posterior arch are fixed with a rod bent in a V-shape.

Gillet's V-shape rod technique offers several advantages over traditional spinal fusion for treating spondylolysis. This technique is minimally invasive, resulting in smaller incisions and reduced tissue damage. As a result, patients often experience a shorter recovery time and less postoperative pain. Unlike spinal fusion, which eliminates movement between vertebrae, the V-shape rod technique permits a certain degree of natural movement, which can be beneficial for maintaining spinal flexibility.

Furthermore, preserving some spinal mobility has been demonstrated to reduce the risk of adjacent segment disease, a condition where the vertebrae above or below the fusion site experience increased stress and degeneration. Studies have shown significant improvement in pain scores and disability indexes with the V-shape rod technique, with benefits maintained over long-term follow-up.[6-8] These advantages position the Gillet's V-shape rod technique as a promising alternative to spinal fusion for certain patient populations with spondylolysis (*Figure 2*).

The most effective method of studying and comparing the mechanical stability of the spine with different instrumentation, is the direct biomechanical cadaver test.[9-13] However, in most cases and in most institutes, this is difficult to perform due to strict regulations and limited possibilities. Finite element analysis, a commonly used numerical method, could help in these cases.[14,15] There have been several studies using finite element analysis to investigate spinal implant-bone systems.[16-19] Turbutz et al[20] investigated two highly accurate CT-based lumbar spine finite element models with identical geometries, but different material models. In the first case, the material model was applied based on the CT-scan density data (i.e. patient-specific model). In the second case, a literature-based material model was implemented. Their validating results proved that both models can be used reliably to model biomechanical properties of the lumbar spine. Most of them accurately model the spine and the metal implants, but there is one factor that is not considered, but could be important.[21] It is the lubricating effect of the human extracellular fluid that penetrates between the metal components and weakens the connections.

The objective of this study was to employ finite element analysis to compare the stability of the spinal fusion and the V-rod technique. A further objective was to evaluate the effect of the friction between the connecting elements of the spinal instrument.

Materials and methods

During the study, the L1-L4 vertebrae with associated discs and implant components were simulated in Ansys v.19 (Ansys, Canonsburg, USA) as shown in *Figure 2* and *Figure 3*.

Geometrical modelling

The three-dimensional model of the vertebrae was reconstructed and exported in VRML (Virtual Reality Modeling Language) using an EOS X-ray imaging system (EOS Imaging, Paris, France).[22] The intervertebral discs were modelled in Inventor Professional v.2025 (Autodesk, San Francisco, USA), using the freeform modelling function, based on our previous method.[23] The outer 2 mm of the vertebra was separated to another model as the cortical bone and the model was remeshed

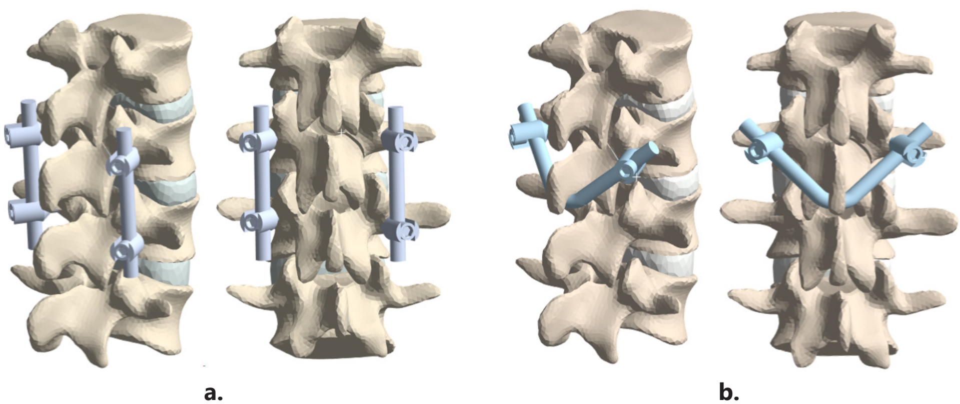

Figure 2. Stabilization techniques for spondylolysis: The spinal fusion (a) and Gillet's V-shape rod technique (b)

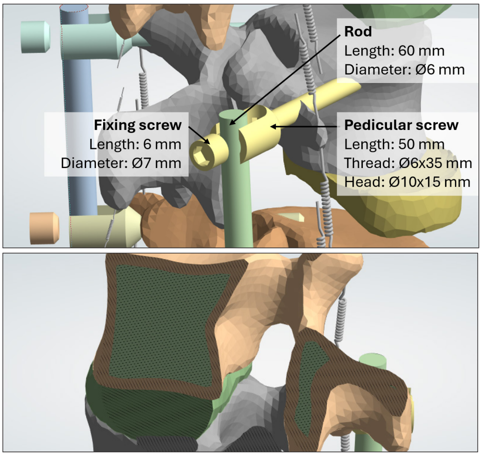

Figure 3. Exploded and section view of the 3D model of the vertebrae-implant system with the dimensions of the components[24]

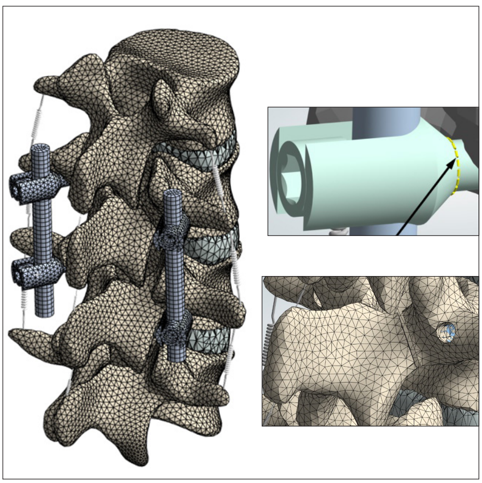

Figure 4. The mesh of the model indicating the fracture cut and the edge, where finer element size was applied

Table 1. Material properties of the components used in the model[25-29]

Item	Material properties
Bone[27]	Cortical: E=12 000 MPa ν= 0.3 Trabecular: E=100 MPa ν = 0.2
Implant (rods and screws)[28]	Ti6Al4V, E = 110 000 MPa ν = 0.3
Intervertebral disc[29]	E=5.36 MPa, ν = 0.45

in each case using 3-Matic v.18 software (Materialise, Leuven, Belgium) (*Figure 3*).

All implant components were modelled in Inventor Professional v.2025 software. As this was not a relevant factor in this case, the geometry of the threads was ignored.

Ansys Spaceclaim was used for the Boolean subtraction of the discs and implants and the assembly of the component. The artificial fracture was constructed in Spaceclaim using a 1 mm cut in L2 (*Figure 4.*).

The finite element model

The meshes of the models were formed built using Tet10 and Hex20. The general element size was set to 3 mm, and 1 mm of edge sizing was applied at the most critical location, at the neck of the screws (*Figure 4*). The material properties were applied according to *Table 1* (E = Young's Modulus [MPa] and ν = Poisson's Ratio).[25,26]

The ligaments were modelled by non-linear tensile-only springs, as described by Rohlmann.[30] The stiffnesses were (depending on strain):

- Anterior longitudinal: 347-1867 N/mm
- Posterior longitudinal: 29.5-236 N/mm
- Intertransverse: 50 N/mm.

The following cases were investigated in the study (*Figure 5*):

1. The L1-L4 lumbar spine without implants: bonded contacts have been applied between the discs and the vertebrae
2. L1-L4 with spinal fusion (*Figure 2.a*)
   a. Bonded case: bonded contacts have been applied between each connected component
   b. Frictional case: frictional contact with friction coefficient of 0.1 was set between the metal components

(rod-pedicular screw, rod-fixing screw) and bonded contacts for the rest of the connections

3. L1-L4 with V-rod fixation (*Figure 2.b*)
   a. Bonded case: bonded contacts have been applied between each connected component
   b. Frictional case: frictional contact with friction coefficient of 0.1 was set between the metal components (rod-pedicular screw, rod-fixing screw) and bonded contacts for the rest of the connections

The facet joints were modelled as frictionless contacts. In accordance with the applied loads, a force of 500 N[15] as the upper body load of an overweight person and a torque of 5 Nm representing the rotation of the spine were utilised to the upper surface of L1 vertebra. The fixed support was placed to the bottom surface of L4 vertebra (*Figure 5*).

Results

The stress distribution with the maximum locations and the vertical deformations are

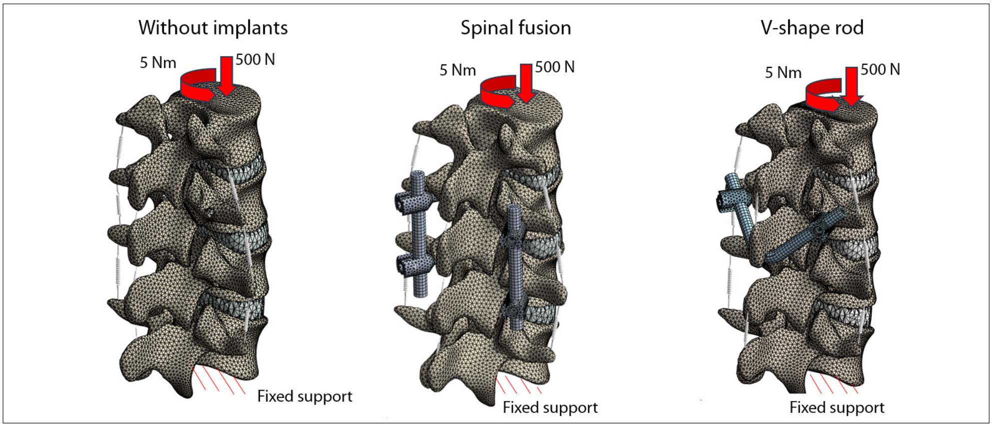

Figure 5. The arrangement and the boundary conditions of the investigated cases

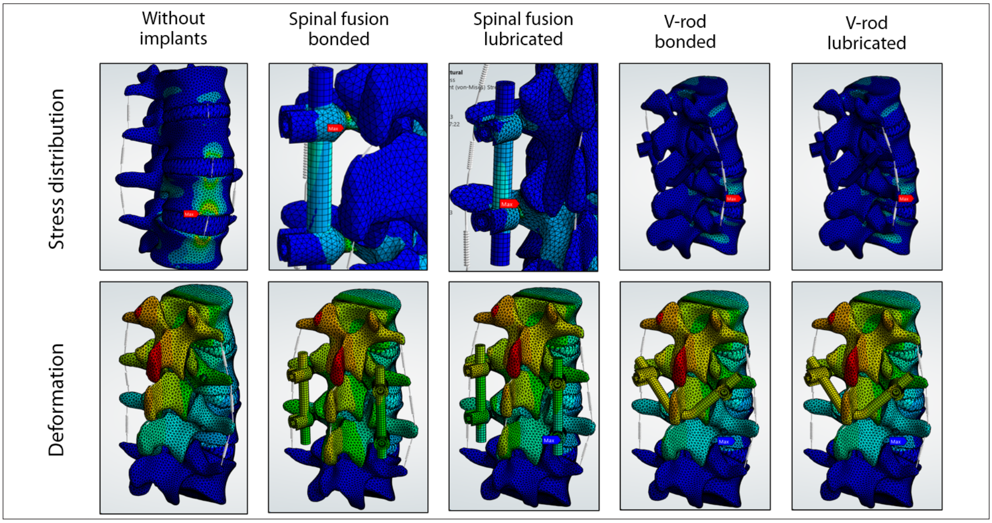

Figure 6. Stress distributions and deformations of the analyses in each case

showed in *Figure 6*. The numerical results of the analyses are summarized in *Table 2*. The fracture opening was determined as the increase in distance between two opposite nodes on the cut surfaces of the fracture.

Discussion

According to the fracture opening, there seem to be no significant differences between the two surgical solutions, suggesting that both techniques are capable of stabilizing the fracture. Concurrently, the vertical deformation of the bonded and frictional cases is different in the case of spinal fusion (9.75 mm vs 11.81 mm). This 21.1% increase demonstrates that the impact of lubrication is a significant factor in the finite element modelling of musculoskeletal implant-bone assemblies.

The results should be assessed in the context of the limitations of the study, which are some aspects of the modelling in terms of simplified discs and cortical/trabecular bone structure compared to in-depth studies[17,20,28] and the lack of validation with real measurements.

Table 2. Numerical results of the analyses

Case	Sub-case	Maximal Von-Mises stress [MPa]	Maximal vertical deformation [mm]	Fracture opening [mm]
Without implants	Only bones and discs	37.1	15.49	0.18
Spinal fusion	bonded contacts	47.6	9.75	0.08
	frictional + bonded contacts	65.3	11.81	0.08
V-rod	bonded contacts	37.1	15.40	0.09
	frictional + bonded contacts	37.3	15.48	0.10

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Conflict of interest: None.

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