Monolithic superelastic rods with variable flexural stiffness for spinal fusion: Simplified finite element analysis of an instrumented spine segment

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Abstract—**Rigid instrumentations have been widely used for spinal fusion but they come with complications, such as adjacent disc degeneration. Dynamic instrumentations have been tested but their efficiency (stabilization capability) and reliability (mechanical integrity of the implant) have yet to be proven. A monolithic Ti-Ni spinal rod with variable flexural stiffness is proposed to reduce the risks associated with spinal fusion while maintaining adequate stabilization. This publication presents a simplified numerical model capable of evaluating the eventual benefits of a Ti-Ni spinal rod with variable flexural stiffness.**

Methods: A simplified instrumented spine segment model composed of six vertebrae and five discs has been developed. Two types of spinal rods were evaluated: Classic Ti instrumentation and Ti-Ni rods with variable stiffness. Both instrumentations were tested using two anchor configurations: pedicle screws only or a screws-cable combination.

Findings and discussion: The all-screws configuration does not allow much motion with either classic Ti or variable Ti-Ni rods. The combination of a Ti rod with screws-cable anchoring allows more motion and, therefore, lower adjacent disk pressure, but puts extremely high stresses on the rod and anchors. The combination of the variable Ti-Ni rod and screws-cable anchoring leads to a significant decrease in adjacent disk pressure, without increasing stresses and pullout forces in the spinal instrumentation.

I. INTRODUCTION

Spinal disorders can be treated by several means including fusion surgery. Rigid posterior instrumentations are commonly used to prevent motion of the instrumented segment and to aid fusion healing [1,2]. Due to the abrupt stiffness variation between the instrumented and intact spinal segments, stresses are increased locally, which leads to adjacent disc degeneration [3]. Dynamic stabilization systems (DSS) have been proposed to lower the stress the risk of adjacent segment degeneration [4]. Clinical studies have shown that "soft" instrumentations are not risk-free: problems related to these implants' loosening, their mechanical failure and poor fusion rate have been reported [5].

An ideal implant would combine static and dynamic properties with the required stiffness where a strong stabilization is needed and more flexible behavior where dynamic properties and load-sharing capacity are important. This combination of properties can be obtained by different methods including the use of Ti-Ni shape memory alloys. The mechanical properties of these alloys are conditioned by their thermomechanical processing [6] and can be controlled by local annealing [7,8].

Our previous study showed that monolithic Ti-Ni rods with variable mechanical properties can be produced using localized Joule-heating heat treatment [9]. Different sections of these rods manifest different behavior, ranging from elastoplasticity (martensitic) to superelasticity (annealed). These technological possibilities allow monolithic spinal rods to be designed with variable flexural stiffness, which would combine stabilization capacity with reduced stress concentration at the implant extremities.

To conduct a preliminary evaluation of the biomechanical implications related to the use of such spinal rods, a simplified numerical model of an instrumented spine segment was developed. The results of this preliminary study are presented in this publication.

II. MATERIALS AND METHODS

A simplified three-dimensional (3D) finite-element model of a spine segment was developed using Ansys 14 commercial software. The model presented in Figure 1 is composed of six vertebrae separated by five discs. The main inputs: the geometry and mechanical properties of the spine (vertebrae, discs), the geometry and mechanical properties of the rod, the configuration of the anchor system, and the mechanical load applied to the spine segment. The vertebrae are modeled as homogeneous solids, whereas the discs are composed of annulus fibrosus and nucleus.

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The spine segment is instrumented with two types of a 3 mm-diameter 90 mm-long rod: a) homogeneous (Ti), and b) half elastic-half superelastic (Ti-Ni) (Figure 1a,b). Note that a smaller, than standard, diameter rod was used in the model to accentuate the effect of variable stiffness on the behavior of the instrumented segment. The Ti rod represents a conventional titanium implant, while the Ti-Ni rod is a novel instrumentation. The rods are attached to the spine using one of two anchors configurations: all-screws (three Ø6mm pedicle screws, Figure 1a) or screws-cable (two Ø6mm pedicle screws and one Ø2mm cable, Figure 1b); all fixation components are made of Ti. The mechanical properties of the model components are collected in Table I. The complete model is meshed with 26453 SOLID186 elements and loaded in forward flexion, lateral bending and axial rotation with imposed rotations of the end-vertebra (V1) of 45°, 45° and 30°, respectively. Figure 2 shows a compilation of the results.

TABLE I. Materials characteristics used in the model

Material	Young's Moduli, GPa	Poisson's ratio
Vertebrae*	0,374	0,3
Discs:** -Annulus fibrosus -Nucleus	 0,03 0,001	 0,45 0,49
Rods: a) Ti b) Ti-Ni: elastic/superelastic	 100 Figure 1c	0,3
Screws, cable (Ti)	100	0.3
*El Masri et al., [10]; **Castellvi et al., [11]		

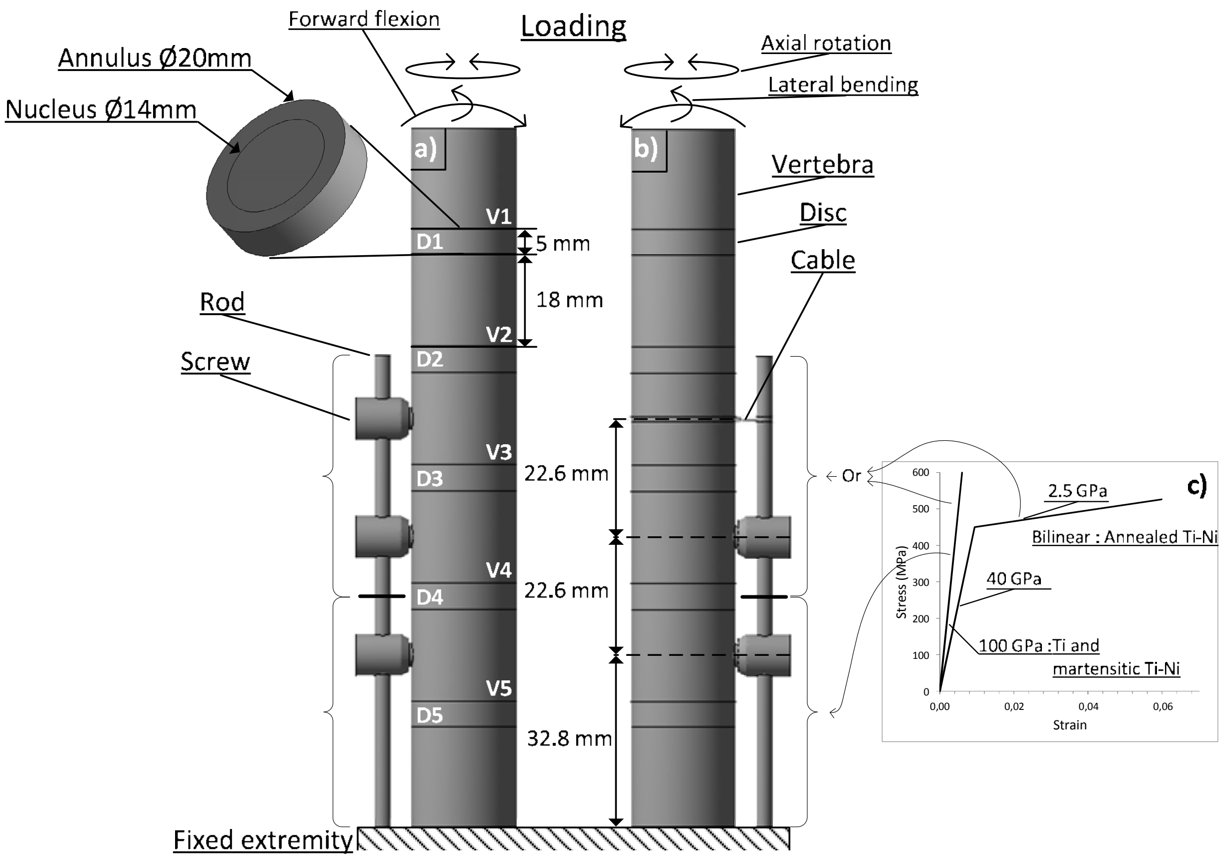

Figure 1. The model's schematic: a) all-screw and b) screws-cable anchoring; c) Stress-strain plots of half elastic-half superleastic (bilinear) and elastic (linear) components.

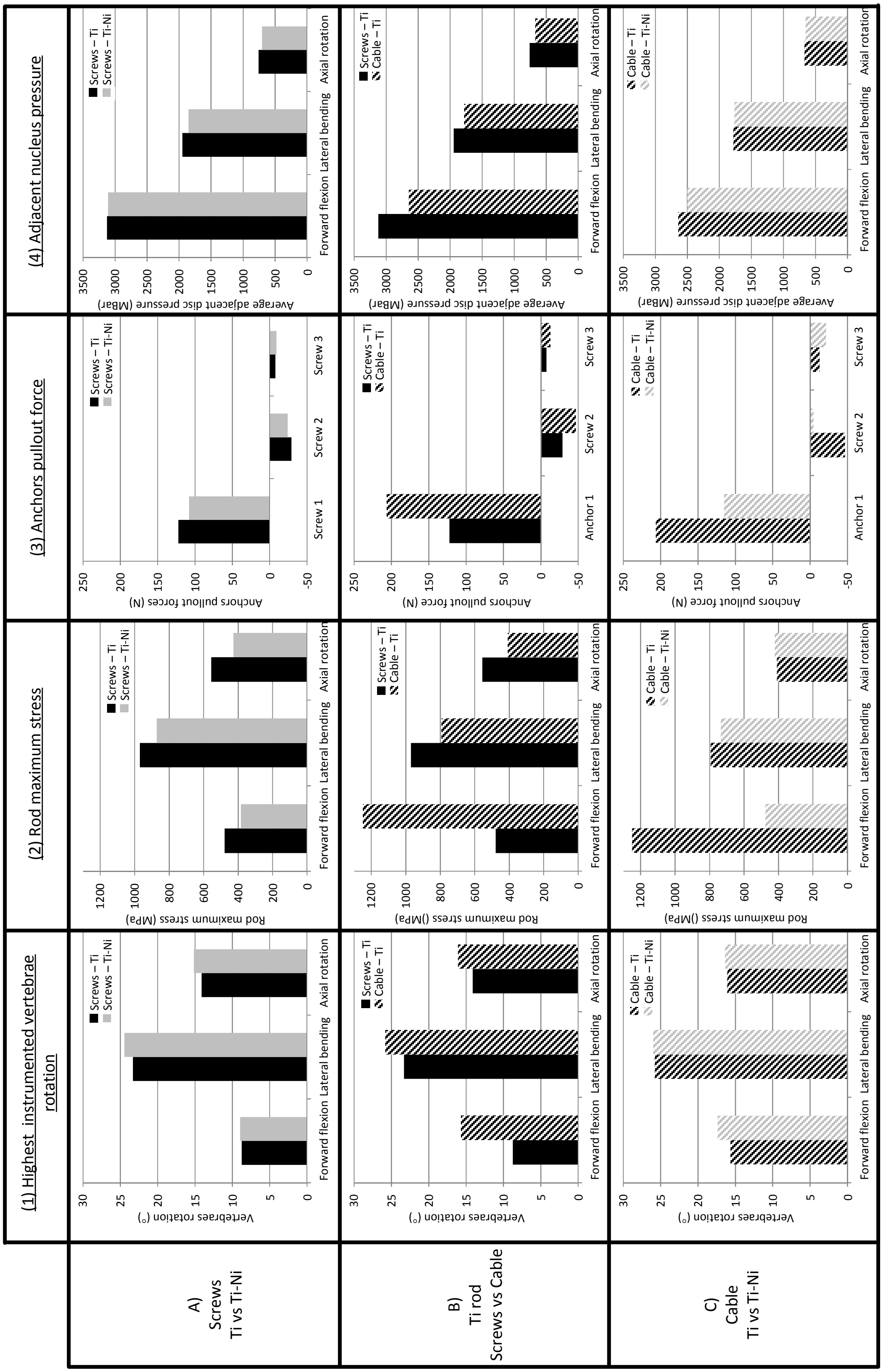

Figure 2. Compilation of the results obtained with the model.

III. RESULTS AND DISCUSSION

Figure 2 presents: (1) the rotation of the top-instrumented vertebra (V3); (2) the maximum stress in the rod; (3) the anchors' pullout force and (4) the average nucleus pressure in the adjacent disc (D2). These four parameters are considered for three motions (forward flexion, lateral bending and rotation) and under three comparative configurations: A) All-screws anchoring: Ti rod *vs* Ti-Ni rod; B) Ti rod: all-screws *vs* screws-cable anchoring; and (C) Screws-cable anchoring: Ti rod *vs* Ti-Ni rod. Note that the pullout forces were only considered for forward flexion, as these values were very weak in lateral bending and rotation.

Case (A) All-screws anchoring: When using only pedicle screws, the impact of the Ti-Ni rod with variable stiffness compared to the homogeneous Ti rod, can be rated as being "moderate-to-weak": The variable-stiffness "softer" implant allows a slightly greater motion of the top-instrumented vertebra, especially in lateral bending (+5%) and axial rotation (+7.8%), which leads to a slightly lower (-5.2 and -6.7%) adjacent disc pressure. The lower pressure output is combined with even lower rod stresses (-10 and -22%). These moderate differences between the homogeneous and heterogeneous rods are due to the all-screws anchoring, which does not allow the top-instrumented vertebra much flexibility of movement, irrespective of the flexural stiffness of the spinal instrumentation.

Case (B) Ti rod: To offer more flexibility to the upper part of the instrumented segment, the highest screw is replaced by less rigid anchor, such as a cable, and this configuration is first tested with the homogeneous implant. It can be seen that the screw-to-cable replacement increases the motion of the top-instrumented vertebra especially in forward flexion (+78%), thus decreasing the adjacent disc pressure (-15%). These benefits are, however, obtained at the expense of extremely high stresses in all of the instrumentation components (rod, screws, cables), potentially leading to instrumentation failure.

Case (C) Screws-cable anchoring: The replacement of the constant-stiffness Ti rod by the variable-stiffness Ti-Ni rod, while keeping the screws-cable anchoring, significantly lowers the stresses and pullout forces, and also reduces the adjacent disc pressure because of the higher mobility of the top-instrumented vertebra.

Using the Ti-Ni rods and screw-cable anchoring (Case C) allows a 20% decrease in adjacent disk pressure (forward flexion), compared to the Ti rods and all-screw anchoring (Case A), without increasing stresses and pullout forces in the spinal instrumentation.

IV. CONCLUSION

This paper proposes a simplified finite element analysis of an instrumented spine segment to assess the eventual biomechanical benefits of variable flexural stiffness Ti-Ni rods. It was shown that the use of a "softer" Ti-Ni rod changes the behaviors of the spine in lateral bending and rotation but not in forward flexion. It was possible to enhance the effects of such rods in all three motions by replacing the highest screw by a cable. With this anchor configuration, the heterogeneous Ti-Ni rod makes it possible to lower the adjacent disc pressure, the stress on the rod and the pullout force applied on the anchors.

To enhance the effect of the Ti-Ni rod in lateral bending and axial rotation, the cable could be replaced by a spinal hook. Further work should lead to the development of a more detailed spine model and its experimental validation. Fusion of the vertebrae should also be considered to improve the model's accuracy. Finally, the mechanical properties gradient of the spinal rod will be optimized to provide to the spine an adequate stabilization, while decreasing the risk of adjacent disk degeneration.

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