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Communication

Finite element analysis of the lumbar destabilization following pedicle subtraction osteotomy

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ABSTRACT

This study aims to analyze the destabilization produced following a pedicle subtraction osteotomy (PSO), with a calibrated numerical model. A 30° resection was created on L3 and L4. Range of Motion (ROM) and the force acting on the vertebral body were calculated. Osteotomies consistently increased the ROMs. In the intact model, 87% of the compressive load was acting on the vertebral bodies whereas in the destabilized models all the load was on the fractured surface. Osteotomies at both levels induced a marked instability but the PSO at L4 seemed to have a greater influence on the ROM. Despite the significant deformity corrections which could be achieved with PSO, this technique needs further analyses.

1. Introduction

Spinal osteotomies are complex surgeries aimed at correcting a pathological spinal curvature. Different techniques were developed (e.g. Ponte osteotomy [1,2] and Smith–Petersen osteotomy [1-3]) all having a great correction power but also a high complications rate [1,2]. Pedicle subtraction osteotomy (PSO), which is mainly used for the treatment of fixed sagittal imbalance, is a posterior closing wedge technique that causes a high correction in a single level (up to 35°). PSO presupposes posterior fixation and the most frequent complications are neurological deficits and hardware failure, in particular rod breakage [1-4].

The aim of this work is to quantify the destabilization produced by a PSO, using a calibrated finite element model of the lumbar spine. This preliminary study is helpful to understand the mechanisms that can contribute to overload the spinal devices used to stabilize the osteotomies, therefore increasing the risk of rod breakage.

2. Material and methods

A non-linear finite element model of the intact lumbosacral spine (L1-S1) was created based on CT scans (512×512 pixels/slice, slice thickness 0.625 mm) of a 40 years old human male (CT scan taken due to kidney stones and not related to spinal pathologies). The position of each vertebra was readjusted mimicking the curvature of a subject having a low lumbar lordosis (35°), thus modeling a case needing surgical correction. Vertebral bodies and intervertebral discs were meshed with linear hexahedral elements whereas the posterior elements were meshed with linear tetrahedrons. Discs were divided in nucleus pulposus, annulus fibrosus and endplates and their heights were consistent with anatomical data [5]. In order to mimic the collagen fibers, four rebar layers were embedded in an isotropic solid matrix [6]. For each layer two bundles of tension-only linear elastic fibers were modeled with orientation of ±30° with respect to the horizontal plane. Moreover, a disc-nucleus volume ratio of about 50% [7,8] and a fiber cross-sectional area of 0.1 mm^2 were assumed [9]. Ligaments were represented as tension-only linear spring elements while the facet joints were modeled with a cartilage layer of 0.2 mm and a gap of 0.6 mm [9]. Mechanical properties (Table 1) were taken from literature [9-12]. Trabecular bone was modeled with transverse isotropic properties. Regarding the ligaments, properties found in literature [13] were modified and adapted during the calibration process (see Supplementary Material). ICEM CFD 14.0 (ANSYS Inc,

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Table 1
Mechanical properties of the different structures of the model.

	Young modulus (MPa)	Poisson coefficient
Cortical bone	12,000	0.3
Trabecular bone	140,140,200	0.45,0.325,0.315
Posterior process	2500	0.25
Cartilage	23.8	0.4
Anulus: fibers	25	0.3
Anulus: ground substance	4.2	0.5
Bony endplates	100	0.4
Nucleus pulposus	1	0.449

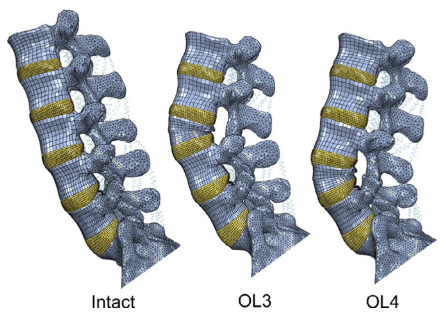

Fig. 1. Intact model of the lumbar spine (left) and osteotomy performed on L3 (middle) and L4 (right).

Canonsburg, PA, USA) was employed to create the mesh while Abaqus 6.12-3 (Dassault Systèmes, Simulia, Providence, RI, USA) was used for the numerical analysis. A mesh convergence study was conducted by monitoring the stresses on the endplates. The final mesh had 215.494 elements and 167.898 nodes. The model was loaded with a follower load of 500 N, by means of connector elements following the spinal curvature. An optimization of the position of the connectors was performed, ensuring a minimization of the rotations (<5%) along the three axes. Pure moments of ±7.5 Nm were applied in flexion-extension, lateral bending and axial rotation to simulate the standing condition, while the inferior part of the sacrum was totally constrained.

All FSUs were calibrated by applying pure moments on the upper surface of the vertebrae, with the inferior endplate and the facets rigidly fixed. The moment/rotation curves as well as the overall Ranges of Motion (ROMs) were compared to literature data [14-21].

Two models were created to simulate the osteotomy on the L3 level (OL3) and on L4 (OL4) (Fig. 1). Since PSO may be used to obtain a correction up to 35° [3,4,22], a wedged shape resection of 30° was performed on the vertebral bodies, resulting in a lumbar lordosis of 65°. A surface-to-surface contact was defined along the fracture extremities with a friction coefficient of 0.46 [23]. To evaluate the influence of the destabilization following a PSO, the ROMs of the intact model (Fig. 3) were compared to the values obtained with OL3 and OL4. Due to the severe destabilization, the osteotomy models did not converge at 7.5 Nm so the comparison was done at the highest moment reached with OL4 (7.5 Nm in flexion, 4 Nm in bending and 3 Nm in extension and axial rotation). The percentage variation of the ROM at the osteotomy level was compared with the ROM of the same level of the intact model (Table 3). Moreover, the forces acting at the osteotomy level in the intact model and on the fractured surface following PSO were calculated after applying the follower load.

3. Results

Comparing the results obtained with the intact model with literature data [15-21], it can be noted that the values of the

Table 2
ROMs and flexibility coefficients of each functional unit.

		Flex	Ext	Left bend	Right bend	Left rot	Right rot
ROM (°)	L1-L2	2.4	1.3	2.6	2.6	2.1	1.7
	L2-L3	2.4	1.5	2.9	2.8	2.1	1.7
	L3-L4	2.6	1.6	2.5	2.3	1.8	1.6
	L4-L5	3.0	2.0	2.6	2.5	1.6	1.5
	L5-S1	4.8	2.8	2.6	2.6	2.1	2.0
Flexibility coefficient (°/Nm)	L1-L2	0.4	0.2	0.4	0.4	0.3	0.3
	[14]	0.5	0.4	0.5	0.5	–	–
	L2-L3	0.6	0.4	0.9	0.9	0.4	0.4
	[14]	0.7	0.3	0.7	0.7	–	–
	L3-L4	0.6	0.3	0.8	0.8	0.3	0.4
	[14]	0.8	0.5	0.9	0.9	–	–
	L4-L5	0.8	0.4	0.7	0.7	0.3	0.3
	[14]	1.0	0.4	0.5	0.5	–	–
	L5-S1	1.2	0.6	0.8	0.7	0.5	0.4
	[14]	1.3	0.8	0.6	0.6	–	–

Table 3
Variation of the ROM, at the osteotomy level, of the two destabilized models (OL3 and OL4). It must be noted that in one case the comparison is at L3-L4 level (model OL3) while the other one is at L4-L5 (model OL4).

ROM variation (%)	OL3 vs intact	OL4 vs intact
Flexion/extension	74	143
Lateral bending	38	327
Axial rotation	61	277

total ROMs in flexion/extension, lateral bending and axial rotation (Table 2 and Fig. 2) are in good agreement. The calculated flexibility coefficients were similar to those found in a previous work [14], with an average error of 14% (Table 2).

After both osteotomies, the global ROMs increased (Fig. 3). The largest variation can be noted in axial rotation (58% for OL3 and 45% for OL4) and lateral bending (43%) for OL4 but all the movements have significant changes (11–16% in flexion/extension). However, the variation of the ROM at the osteotomy site is even more pronounced (Table 3).

Moreover, the load acting on L3 and L4 was 85% and 87% of the total follower load while in the osteotomy models (OL3 and OL4), as expected following the removal of the posterior structures of the spine, 500 N were insisting on the fracture.

4. Discussion

This study, represents the first and key step to understand the behavioral changes in a spine subjected to PSO, and helps to compare the different fixation system and hardware constructs. Several osteotomy techniques are currently used but they are all technically demanding and imply a high rate of complications, which may be related to biomechanical factors [1-4,22,24]. Nevertheless, only few biomechanical studies are available in the literature. In a published study, Ponte osteotomy and discectomy were compared in terms of ROM and posterior translation of the vertebral segments with respect to the intact situation. The authors found that a Ponte osteotomy causes a 20% destabilization while a total discectomy is even more severe [25]. Hato et al. studied a closing-opening correction osteotomy with a numerical model of the thoraco-lumbar spine [26]. Several models were created, considering different grades of osteoporosis and varying the kyphotic angle but the results are not directly comparable with the present paper, due to the different surgical techniques investigated. Charosky et al. studied the PSO with a simplified computational model, reproducing three defect situations and studying loads and stresses arising in different configurations of spinal implants [27].