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Effect of a pedicle-screw-based motion preservation system on lumbar spine biomechanics: A probabilistic finite element study with subsequent sensitivity analysis

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A B S T R A C T

Pedicle-screw-based motion preservation systems are often used to support a slightly degenerated disc. Such implants are intended to reduce intradiscal pressure and facet joints forces, while having a minimal effect on the motion patterns.

In a probabilistic finite element study with subsequent sensitivity analysis, the effects of 10 input parameters, such as elastic modulus and diameter of the elastic rod, distraction of the segment, level of bridged segments, etc. on the output parameters intervertebral rotations, intradiscal pressures, and facet joint forces were determined. A validated finite element model of the lumbar spine was employed. Probabilistic studies were performed for seven loading cases: upright standing, flexion, extension, left and right lateral bending and left and right axial rotation.

The simulations show that intervertebral rotation angles, intradiscal pressures and facet joint forces are in most cases reduced by a motion preservation system. The influence on intradiscal pressure is small, except in extension. For many input parameter combinations, the values for intervertebral rotations and facet joint forces are very low, which indicates that the implant is too stiff in these cases. The output parameters are affected most by the following input parameters: loading case, elastic modulus and diameter of the elastic rod, distraction of the segment, and angular rigidity of the connection between screws and rod.

The designated functions of a motion preservation system can best be achieved when the longitudinal rod has a low stiffness, and when the connection between rod and pedicle screws is rigid.

1. Introduction

In contrast to rigid spinal stabilization devices, pedicle-screw-based motion preservation systems are intended to maintain most of the natural intervertebral range of motion. Slightly degenerated discs are often treated with motion preservation systems to slow down or even stop further degeneration. It is assumed that a dynamic stabilization system allows for a motion pattern similar to that of a healthy motion segment, a strong reduction in facet joint forces during extension, and a reduced intradiscal pressure during flexion and extension. Thus, pedicle-screw-based implants for dynamic stabilization of the lumbar spine are becoming more and more popular (Ahn et al., 2008; Schmoelz et al., 2006; Stoll et al., 2002; Wilke et al., 2009). The stabilizing effect of the early and wide-spread Dynesys device, however, differs only slightly from that of a rigid metallic fixation device, (Rohlmann et al., 2007).

Schmoelz et al. (2009) experimentally studied the behaviour of the novel Elaspine non-fusion implant (Spinelab AG, Winterthur, Switzerland), which is comprised of pedicle screws and a clip mechanism connected to a polycarbonate-urethane (PCU) rod with a 360° form-fit. Six fresh lumbar spine specimens were tested and the results of the Elaspine implant were compared to those of the Dynesys system (Zimmer, Winterthur, Switzerland) as well as to the intact situation. Compared to published data for the Dynesys system (Schmoelz et al., 2003), the Elaspine implant allowed greater motion in lateral bending and flexion/extension while still exhibiting a limited range of motion compared to the intact spine. Both implants had a minor effect during axial rotation.

The influence of implant stiffness on the mechanical behaviour of the lumbar spine was evaluated in a deterministic finite element study (Rohlmann et al., 2007). It was found that only implants with a very low stiffness allow significant motion in the treated segment during flexion and extension.

The influences of an implant on intervertebral rotation, facet joint forces, and intradiscal pressure may depend on several

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factors including implant stiffness, distance of the longitudinal rod from the vertebra, number of treated segments, extent of the bony defect, distraction of the segment, etc. These influences may be strongly increased by combinations of several factors. The combination of all possible values for these factors leads to a very large number of possibilities making it impractical to investigate. In probabilistic finite element studies, calculations are performed for a large number of random parameter combinations and the possible range of results is estimated (Dar et al., 2002; Haldar and Mahadevan, 2000). A subsequent statistic sensitivity analysis allows the determination of those factors, which mainly explain the variance of the results.

The aims of the present study were twofold: (1) to determine in a probabilistic study the possible ranges of the output parameters intervertebral rotation, facet joint force, and intradiscal pressure for 10 input parameters, such as elastic modulus and diameter of the longitudinal rod, angular rigidity of the stabilization device, number of stabilized segments, etc.; and (2) to calculate in a subsequent sensitivity analysis the coefficients of importance (CoIs) in order to determine the influence of single input parameters on the variance of the output parameters.

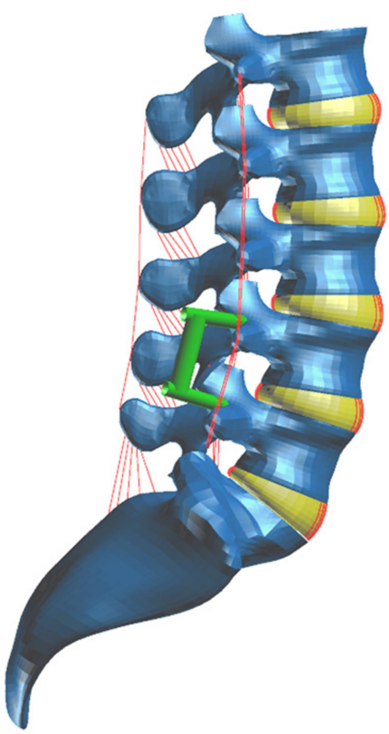

Fig. 1. Finite element model of the lumbar spine with a pedicle-screw-based motion preservation system at level L4/L5.

2. Methods

2.1. Finite element model of the lumbar spine

A previously validated osseoligamentous finite element model of the lumbar spine was employed, consisting of 5 vertebrae, 5 intervertebral discs, and 8 ligaments (Rohlmann et al., 2007; Zander et al., 2009, 2001) (Fig. 1). The annulus fibrosus of the discs was modelled as fibre-reinforced hyperelastic composite. The fibres were embedded in the ground substance in concentric rings around the nucleus pulposus. The nucleus was simulated as a cavity filled with incompressible fluid. All eight major ligaments of the lumbar spine were included in the model. They were represented by tension-only spring elements with non-linear material properties. The fibres and ligaments have been described in detail elsewhere (Nolte et al., 1990; Rohlmann et al., 2006; Shirazi-Adl et al., 1986). The geometry of the vertebrae was taken from computer tomography scans. During bending and rotation of the lumbar spine, most of the motion occurs in the intervertebral disc. Thus, to reduce computational time, in the present study, the bones were assumed to be rigid. The curved facet joints had a thin cartilaginous layer and a gap of 0.5 mm in the unloaded neutral position. They were only able to transmit compressive forces. Material properties of the different tissues were taken from the literature (Table 1). Pedicle-screw-based motion preservation systems of different lengths were inserted. The screws were firmly connected to the vertebrae. All implants bridged at least the disc L4/L5. The pedicle screws (titanium) and elastic rods (PCU) were modelled using beam elements.

2.2. Loading

The seven loading cases: upright standing, flexion, extension, left and right lateral bending, and left and right axial rotation were studied. Upright standing was simulated by applying a follower load of 500 N (Rohlmann et al., 2009a). For simulating flexion, a follower load of 1175 N and a flexion bending moment of 7.5 N m were chosen (Rohlmann et al., 2009b). For extension, lateral bending, and axial rotation, a follower load of 500 N and a moment of 7.5 N m were assumed. Such moments are recommended by Wilke et al. (1998) for spinal implant testing. The caudal endplate of the disc L5-S1 was rigidly fixed.

2.3. Probabilistic study

The following 10 parameters were simultaneously randomized for each loading case.

(a) Elastic modulus of longitudinal rod: values for PCU varied between 5 and 1600 MPa.
(b) Diameter of the longitudinal rod: the permitted range was 4–15 mm.
(c) Angular rigidity of the pedicle screw head: one rigid pedicle screw head and one with a pivot connection having no resistance were studied. In the latter case, all rod rotations were allowed except axial rotation.
(d) Distance between longitudinal rod and pedicle entrance: the permitted range was 4–20 mm.
(e) Convergence of pedicle screws: the screws on the left and right side were inserted nearly parallel (160°), slightly convergent (140°), or strongly convergent (100°).
(f) The implant also bridges the cranial level L3/L4: yes or no.
(g) The implant also bridges the caudal level L5/S1: yes or no.
(h) Distraction of the spinal segment by increasing the effective rod length: the permitted range was between 0 and 2 mm. All segments bridged by the implant had the same distraction.
(i) Defect model: intact spines, right-sided facetectomy (removal of the processus articularis inferior), bilateral facetectomy as well as laminectomy (additional transaction of the lig. supraspinale, lig. interspinale, and lig. flavum) were studied. The defect was always set at all implant levels.

Table 1
Material properties and element types used for the different tissues.

Component	Elastic modulus (MPa)	Poisson ratio (–)	Element type	References
Bone	Rigid			
Ground substance of annulus fibrosus	Hyperelastic, neo-Hookean $C_{10}=0.3448$, $D_1=0.3$		8-Node Hex	Abaqus (2008), Eberlein et al. (2000)
Fibres of annulus fibrosus	Non-linear and dependent on the distance from the disc centre		Rebar	Shirazi-Adl et al. (1986)
Ligaments	Non-linear		Spring	Nolte et al. (1990), Rohlmann et al. (2006)
Cartilage of facet joint	Soft contact			Sharma et al. (1995)
Pedicle screws	110,000	0.3	Beam	
Longitudinal rod	Variable	0.3	Beam	