Impact of material and morphological parameters on the mechanical response of the lumbar spine – A finite element sensitivity study

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Abstract

Finite element models are frequently used to study lumbar spinal biomechanics. Deterministic models are used to reflect a certain configuration, including the means of geometrical and material properties, while probabilistic models account for the inherent variability in the population. Because model parameters are generally uncertain, their predictive power is frequently questioned. In the present study, we determined the sensitivities of spinal forces and motions to material parameters of intervertebral discs, vertebrae, and ligaments and to lumbar morphology. We performed 1200 model simulations using a generic model of the human lumbar spine loaded under pure moments. Coefficients of determination and of variation were determined for all parameter and response combinations. Material properties of the vertebrae displayed the least impact on results, whereas those of the discs and morphology impacted most. The most affected results were the axial compression forces in the vertebral body and in several ligaments during flexion and the facet-joint forces during extension. Intervertebral rotations were considerably affected only when several parameters were varied simultaneously. Results can be used to decide which model parameters require careful consideration in deterministic models and which parameters might be omitted in probabilistic studies. Findings allow quantitative estimation of a model’s precision.

1. Introduction

Finite element (FE) simulations are frequently used in lumbar spinal biomechanics. However, simulations always require simplifications and estimations, because model parameters are numerous, often only vaguely known and too complex to implement. Their impact on responses is a priori unknown and complete validation is mostly impossible (Oreskes, 1998). Therefore, the need for sensitivity analyses has been indicated (Anderson et al., 2007; Ayturk and Puttlitz, 2011; Viceconti et al., 2005). The smaller the impact of uncertain parameters on model responses, the more reliable it can be considered. In contrast, parameters with high impact on responses require careful consideration, particularly when creating models representing an average or even an individual situation.

Knowledge about a model’s sensitivities is furthermore advantageous in probabilistic models with a high number of parameters, which are varied according to their population-based natural probability and combined with each other. For each combination in the design space, a simulation must be performed. The results of all simulations provide the requested result distribution. Parameters with a marginal impact do not need to be varied, thereby reducing the dimensionality of the design space and thus the modelling, computational, and evaluation efforts.

Occasionally, model calibration is required (e.g., Garo et al., 2011; Malandrino et al., 2009; Schmidt et al., 2006), with the model being fitted to measurements. This parameter identification by inverse modelling can only be solved if the parameters influencing the model responses are known. When more “responsible” parameters have to be determined than experimental results exist, the problem is under-determined and can generally not be uniquely solved.

Finally, sensitivity analyses provide an insight into the robustness of deterministic FE studies that do not consider probability distributions, rather use a fixed configuration. Such analyses show the results’ robustness with respect to model parameter variations. Due to the complexity of probabilistic approaches, deterministic models are still most commonly used. In 2008, Jones and Wilcox systematically summarised existing sensitivity studies. Current
pre-processors simplify geometrical variations, which have since been performed by considering the dimensions of vertebrae, discs, and ligaments (Cappetti et al., 2016; Meijer et al., 2011; Niemeyer et al., 2012) or by sophisticatedly creating a set of shape modes (Campbell and Petrella, 2016). In addition to systematically investigating certain geometrical parameters, there are studies investigating several distinct spinal shapes (Campbell et al., 2016; Naserkhaki et al., 2016; Zanjani-Pour et al., 2016).

The present study aims to investigate and compare the model sensitivities of disc, bone, and ligament material properties as well as of distinct spinal morphologies between and among themselves for the intervertebral rotations, intradiscal pressures, axial-section forces, and forces in the ligaments and facet joints.

2. Material and methods

2.1. Finite element model

A previously developed FE model of the lumbar spine for L1–L5 served as the basis for all analyses. The model was validated using in vitro data for both intra-segmental and intralumbar motions, for intradiscal pressure, and for facet-joint forces (partly shown in Fig. 3). Furthermore, the model delivers results comparable with those of other research groups. Further details are provided elsewhere (Dreischarf et al., 2014; Zander et al., 2009; Zander et al., 2007).

The basic model contains five vertebrae, four intervertebral discs, and seven ligaments. The vertebrae consist of the posterior structures, cortical shell, and spongious bone in the vertebral bodies. The seven lumbar ligaments are modelled as one-dimensional force elements (Rohlmann et al., 2006). The discs consist of the nucleus, annulus ground substance, annulus fibres, and cartilaginous endplates.

![Fig. 1. Parameters and responses of the sensitivity analyses.](image)

<table>
<thead>
<tr>
<th>Parameter groups</th>
<th>Assumed characteristic</th>
<th>Varied parameter</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc parameters (IVD)</td>
<td>Hydrostatic</td>
<td>Bulk Modulus</td>
<td>2233 MPa</td>
<td>1116 ... 3350 MPa</td>
</tr>
<tr>
<td>Nucleus compressibility</td>
<td>Neo-Hooke hyperelastic</td>
<td>Neo-Hooke C10</td>
<td>0.3448</td>
<td>0.1724 ... 0.5172</td>
</tr>
<tr>
<td>Annulus matrix</td>
<td>Neo-Hooke D1</td>
<td>0.3</td>
<td>0.15 ... 0.45</td>
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</tr>
<tr>
<td>Fibres</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Stress scale factor</td>
<td>1.0</td>
<td>0.5 ... 1.5</td>
</tr>
<tr>
<td>Bone parameters (OSS)</td>
<td>Isotropic elastic</td>
<td>Young's modulus</td>
<td>3500 MPa</td>
<td>1175 ... 5250 MPa</td>
</tr>
<tr>
<td>Posterior region</td>
<td>Isotropic elastic</td>
<td>Young's modulus</td>
<td>10,000 MPa</td>
<td>5000 ... 15,000 MPa</td>
</tr>
<tr>
<td>Cortical shell</td>
<td>Transverse isotropic</td>
<td>Axial Young's modulus</td>
<td>200 MPa</td>
<td>100 ... 300 MPa</td>
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<tr>
<td>Spongious bone</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
<td>1.0</td>
<td>0.5 ... 1.5</td>
</tr>
<tr>
<td>Anterior longitudinal ligament (ALL)</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
<td>1.0</td>
<td>0.5 ... 1.5</td>
</tr>
<tr>
<td>Posterior long. ligament (PLL)</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
<td>1.0</td>
<td>0.5 ... 1.5</td>
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<tr>
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<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
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<td>0.5 ... 1.5</td>
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<tr>
<td>Intertransverse ligament (ITL)</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
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<td>0.5 ... 1.5</td>
</tr>
<tr>
<td>Facet capsular ligament (FCL)</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
<td>1.0</td>
<td>0.5 ... 1.5</td>
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<tr>
<td>Interspinous ligament (ISL)</td>
<td>Nonlinear stress–strain characteristic</td>
<td>Force scaling factor</td>
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<td>0.5 ... 1.5</td>
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<td>Supraspinous ligament (SSL)</td>
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<td>Force scaling factor</td>
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<td>0.5 ... 1.5</td>
</tr>
<tr>
<td>Morphological parameters (MOR)</td>
<td>According to Roussouly et al. (2005)</td>
<td>“Type”</td>
<td>Default</td>
<td>1, 2, 3, 4</td>
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<td>Spinal shape</td>
<td>Exponential pressure-clearance law</td>
<td>Gap distance</td>
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<td>0 ... 0.5 mm</td>
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<tr>
<td>Joint gap distance</td>
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<td></td>
<td></td>
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</tr>
</tbody>
</table>

![Image](image)
2.2. Sensitivity analyses

The default model was made generic to allow for sensitivity analyses of intervertebral-disc, bone, and ligament parameters and for morphological variations (Fig. 1). Table 1 provides an overview of all the investigated parameters, the constitutive material laws, and the ranges covered, and shows to which of the four indicated groups the varied parameters were assigned. The ranges were chosen between 50% and 150% of the default to represent a reasonable area around the validated configuration. Morphological variations reflect the four lumbar shapes described by Roussouly et al. (2005) and the gap distance between the facet-joint surfaces. Variations principally refer to the sacral slope, lumbar lordosis, and apex of lordosis. Morphometric details are provided elsewhere (Dreischart et al., 2015). In total, 1200 FE analyses were performed to obtain a confidence interval of $0.1$ for a coefficient of determination (CoD) of 0.7 at a 95% confidence level (Bucher, 2009). Latin hypercube sampling was performed to reduce the necessary number of samples. In addition to evaluating CoDs for linear correlations, those for quadratic correlations were analysed to identify non-linear behaviour. The coefficient of variation was used to determine the relevance of the response range. Table 2 lists the load cases taken into account to calculate the mean responses used as reference values for the coefficients of variation (non-existing facet-joint forces during flexion were, for example, not taken into account). Sampling and statistical evaluation were performed using OptiSLang 4.2.2 (Dynardo GmbH, Germany).

2.3. Model simulations

The nonlinear, implicit FE analyses were performed using Abaqus/Standard 6.12.4 (Dassault Systèmes Simulia GmbH, Germany). All models were subjected to pure moments of 7.5 Nm in flexion, extension, lateral bending, and axial rotation (Fig. 1).

The most frequent model outputs of spinal FE investigations were considered: intradiscal pressure, axial force in the vertebral body, contact force in the facet joints, forces in the ligaments, and intervertebral rotations at level L4 or L4/L5, respectively. The total range of results is provided for all four load cases and all four parameter groups for the whole range of loading between 0 and 7.5 Nm. Furthermore, the CoDs are provided for the maximum load (7.5 Nm) for all investigated parameters and responses.

3. Results

3.1. Influence of parameter groups

The amount of loading influenced the impact of the studied parameter groups (Fig. 2). In general, the intradiscal pressure was strongly affected by the intervertebral-disc parameters. The influence of bone and ligament parameters was, in general, small. The morphology also displayed a strong influence, except for flexion, where ligaments played a greater role (Figs. 2 and 3). Similar results were obtained for the axial-section force. In extension, the morphology had the strongest effect. Extension, axial rotation, and small lateral-bending moments resulted in tensile section forces. Facet-joint forces were dominated by the morphology. They were largest in axial rotation, zero in flexion and, depending on the initial joint-gap distance, zero in lateral bending and extension. The effect of other parameter groups was relatively

![Figure 2](image-url)
Intervertebral rotations were little affected, particularly by bone parameters. The largest effect was caused by disc parameters, particularly for lateral bending and small moments during flexion, followed by morphological parameters. Anterior longitudinal ligament forces were predicted mainly during extension (Fig. 3). The response ranges were similar for all parameter groups. The contra-lateral intertransverse ligament mainly resisted lateral bending. Disc-parameter variation led to the largest response range. The facet capsular ligament was the only ligament active for all load cases, with maximum loads during axial rotation and mostly influenced by disc and morphological parameters. Posterior longitudinal, flaval, inter-, and superspinous ligaments were only tense during flexion and mostly affected by ligament and morphological parameters.

3.2. Coefficients of determination for maximum load

Overall, only a few responses were markedly correlated to the parameters, and none of the quadratic was significantly superior to the linear approximations: 80% of all combinations displayed a CoD $\leq 0.2$ (Fig. 4) and several of the combinations with a high CoD showed a small effect. The posterior bone modulus of elasticity, for example, was strongly correlated to the facet-joint forces during lateral bending (CoD=0.91) but showed a range of forces over only 2 N (44–46 N). In the following, the only combinations described were those which showed a CoD $> 0.5$ and a coefficient of variation $> 10\%$ (Fig. 4). For disc parameters, only the annulus coefficient C10 was relevant. A decrease substantially increased the intradiscal pressure for all load cases, except for axial rotation. C10 further increased the axial force in the vertebra for lateral bending and flexion, and influenced some ligament forces for certain load directions. Variation of bone material properties displayed in general the least influence on investigated model responses. Ligament stiffnesses mostly influenced the forces within themselves. A weak anterior longitudinal ligament additionally considerably reduced the intradiscal pressure during extension.

The morphology essentially affected the intradiscal pressure during lateral bending and extension, the axial-section force during lateral bending and flexion, the contact force, and the force in the intertransverse ligament during lateral bending. A larger joint-gap distance markedly reduced the axial tensile force and the facet-joint force during extension as well as the latter during axial rotation.

4. Discussion

By definition, models contain assumptions whose uncertainties reduce predictive power by an unknown degree. This study aimed to provide answers to what degree imprecise (with respect to an individual) and variable assumptions of a static lumbar-spine FE model (with respect to a population) influence predictions. Several material and morphological parameters were investigated in sensitivity analyses with variations lying centrally around the default configuration of a validated FE model. Bone properties, particularly those of vertebral bodies, appear to be of less importance for the studied responses because they are magnitudes stiffer than discs and ligaments. The largest impact of studied bone properties was determined for the posterior structures because of their small cross-sectional area and large bending moments.
caused by ligament and facet-joint forces. Once the ligaments’ slack lengths are calibrated to fit experimental intervertebral rotations, scaling of the ligament forces mainly influences the force they have to exert. Their influence on other parameters was generally not very pronounced. This might be due to the flat slope at the beginning of their exponentially increasing force strain characteristic and is in accordance with the findings of Heuer et al. (2007). For larger loads and different slack lengths, ligament force scaling could have a greater impact.

Disc and morphological parameters displayed the greatest influence. This is in accordance with several studies, which reported the strong effect of facet-joint morphology (Heuer et al., 2007; Holzapfel and Stadler, 2006; Maurel et al., 1997; Naserkhaki et al., 2016; Noailly et al., 2007). From this point of view, so-called patient-specific models, which is a term often used as a synonym for patient-specific morphologies, are reasonable. However, overall disc stiffness depends on material as well as on morphology, and it appears likely that there are interdependencies (Cappetti et al., 2016; Maquer et al., 2014). Patient-specific modelling would additionally require knowledge about individual loading. Preloading of the spine, for example, shows a remarkable influence on kinematics (Renner et al., 2007; Weisse et al., 2012). In the current study, we maintained constant loading. Adapting the loading to keep rotations constant, for example, would lead to different results. However, loading is frequently not considered a model parameter. If investigated in broader detail, load variations should always be studied in combination with other parameter variations, as was performed here only for the different load directions.

With respect to morphology, the current study focused on facet-joint distances and five distinct spinal shapes. More detailed variations in morphologies, as investigated by Niemeyer et al. (2012) and Cappetti et al. (2016), require a new mesh generation for each geometry and a subsequent mesh-density convergence analysis. This is seldom performed (Ayturk and Puttlitz, 2011) and was beyond the scope of the present study. Due to that limitation the sensitivity of the results to other morphological changes is not known.

The number and possible combinations of model parameters even when limited to statics are tremendous. This reflects the complexity of the geometry in addition to the material behaviour, which might even be simulated by different material laws. Therefore, the present study comprised some parameters, which can readily be adapted in future FE models. Only pure moments were studied, as in many in vitro studies. Other loads, including compression and shear forces, would alter the predicted responses and sensitivities. Results were evaluated at L4/L5 level. Due to other geometrical dimensions and orientations somewhat different results can be expected at other lumbar levels. Only CoDs > 0.5 and CoVs > 10% were discussed. Even lower limits or reference values (Table 2) would indicate more results as relevant.

Within the considered results, loads, and indicated limitations, excluding bone elasticity did not markedly alter the predictions.
Morphology, particularly facet-joint gap distance, and intervertebral discs should be modelled as precisely as possible according to the investigated specimens, because they strongly influence results. Considerable variations in intersegmental rotations can only be expected when simultaneously varying several model parameters of discs, ligaments, and morphology.

Conflict of interest statement

All authors declare that there are no financial or personal relationships with other persons or organisations that could have inappropriately influenced this study.

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