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Comparison of eight published static finite element models of the intact lumbar spine: Predictive power of models improves when combined together

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ABSTRACT

Finite element (FE) model studies have made important contributions to our understanding of functional biomechanics of the lumbar spine. However, if a model is used to answer clinical and biomechanical questions over a certain population, their inherently large inter-subject variability has to be considered. Current FE model studies, however, generally account only for a single distinct spinal geometry with one set of material properties. This raises questions concerning their predictive power, their range of results and on their agreement with *in vitro* and *in vivo* values.

Eight well-established FE models of the lumbar spine (L1-5) of different research centers around the globe were subjected to pure and combined loading modes and compared to *in vitro* and *in vivo* measurements for intervertebral rotations, disc pressures and facet joint forces.

Under pure moment loading, the predicted L1-5 rotations of almost all models fell within the reported *in vitro* ranges, and their median values differed on average by only 2° for flexion-extension, 1° for lateral bending and 5° for axial rotation. Predicted median facet joint forces and disc pressures were also in good agreement with published median *in vitro* values. However, the ranges of predictions were larger and exceeded those reported *in vitro*, especially for the facet joint forces. For all combined loading modes, except for flexion, predicted median segmental intervertebral rotations and disc pressures were in good agreement with measured *in vivo* values.

In light of high inter-subject variability, the generalization of results of a single model to a population remains a concern. This study demonstrated that the pooled median of individual model results, similar to a probabilistic approach, can be used as an improved predictive tool in order to estimate the response of the lumbar spine.

1. Introduction

Accurate and clinically relevant modeling of complex biological systems such as the human lumbar spine remains challenging, yet promising, with the potential to substantially enhance the quality of patient care. Due to its ability to represent intricate systems with material nonlinearities, irregular loading, and geometrical and material domains, the finite element (FE) method has been recognized as an important computational tool in various biomedical fields (Zhang and Teo, 2008) and has been widely adopted for describing spinal biomechanics (Schmidt et al., 2013). In comparison to *in vitro* or *in vivo* approaches, computational methods are advantageous in offering cost efficient and powerful response solutions while at the same time effectively dealing with the ethical concerns related to the use of live animals in experiments. Moreover, use of computational models may greatly diminish the

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need for experimental investigations that utilize *post mortem* human and animal specimens. For example, finite element models provide improved insight into the functional mechanisms of the spine by assessing the isolated effect of various parameters independently – a feature that has been invaluable with respect to the design/optimization of spinal implants (Fagan et al., 2002a; Schmidt et al., 2013; Zhang and Teo, 2008).

Despite the proven success of computational studies in other disciplines, the FE method's role in clinical spine research has sometimes been questioned (Viceconti et al., 2005). The uncertainty and high variability of tissue material properties, the anatomical complexity of spinal structures (Panjabi et al., 1992, 1993), and the unknown loading (Rohlmann et al., 2009; Wilke et al., 1998) and boundary conditions, particularly *in vivo*, has cast doubt on the accuracy and reliability of FE model predictions. The inherent geometric and material property differences among individuals and alterations in these parameters due to age, sex and degeneration may limit the widespread applicability of the reported results. To gain confidence in and to enhance the predictive quality of FE models, recommendations have been made on how to develop suitable models in order to address research questions within an adequate degree of predictive accuracy (Anderson et al., 2007; Jones and Wilcox, 2008; Oreskes et al., 1994; Roache, 1998; Viceconti, 2011; Viceconti et al., 2005). These standards comprise three main steps: code verification, sensitivity analyses of uncertain model input parameters, and task-specific validations of the model.

The verification of the code poses the least concern as the vast majority of computational studies nowadays employ extensively verified, commercially available FE software. The analysis of the sensitivity to alterations in geometrical (Dupont et al., 2002; Meijer et al., 2011; Natarajan and Andersson, 1999; Niemeyer et al., 2012; Noailly et al., 2007; Robin et al., 1994), material (Fagan et al., 2002b; Lee and Teo, 2005; Rao and Dumas, 1991; Shirazi-Adl, 1994a; Zander et al., 2004) or loading parameters (Dreischarf et al., 2011; 2012; Rohlmann et al., 2009); however, demands more time and effort and has hence only occasionally been carried out. It has been shown that the range of motion (RoM) of a lumbar motion segment is strongly affected by the disc height (Meijer et al., 2011; Natarajan and Andersson, 1999; Niemeyer et al., 2012; Robin et al., 1994) and material properties (*e.g.* ligament properties (Zander et al., 2004). Furthermore, appropriate loading conditions (Dreischarf et al., 2011, 2012) are necessary to realistically simulate relevant tasks under maximal voluntary motion measured *in vivo* (Pearcy, 1985; Pearcy et al., 1984; Pearcy and Tibrewal, 1984; Wilke et al., 2001).

The term 'validation' merits attention as it remains controversial. Validation is commonly used to indicate that model predictions are consistent with observations. However, it is intractable to completely validate numerical models because it is not possible to account for the multiplicity of their inherent degrees of freedom in an experiment (Oreskes et al., 1994). It is, however, generally accepted that greater number and diversity of corroborating observations between a model and experimental data increases the probability that the model predictions are not flawed (Oreskes et al., 1994; Viceconti et al., 2005). To increase the confidence in a model, the number of free independent parameters employed to construct the model should remain low to decrease the risk of non-uniqueness. Detailed experimental data on the lumbar spine that would allow for a thorough validation of model predictions remain, however, limited. For example, measurements are often only performed at a single level. Model validation is therefore often performed by comparing the calculated results with the limited data that is available from *in vitro* studies (Moramarco et al., 2010; Zander et al., 2009). However, experimental setups, specimens, loading and boundary conditions substantially differ among various studies (Brinckmann and Grootenboer, 1991; Kettler et al., 2011; Rohlmann et al., 2001b; Wilke et al., 1994), and these differences are often neglected with regard to the resulting data. Furthermore, the validation of numerical models should preferably include as many relevant outputs as possible (Woldtvedt et al., 2011), as some may be more sensitive to model assumptions than others under specific loading conditions. Moreover, for clinically relevant parameters such as the facet joint forces (FJF), which have considerable dependence on loading and geometry, almost no *in vivo* data exist (Wilson et al., 2006).

Well-established FE models should incorporate the aforementioned three steps to meet the conditions for a meaningful numerical study. Despite these requirements, most FE studies account for only one spinal geometry with one set of material properties and are validated with very few available experimental data. This raises questions with regard to the reliability/comparability of their predictions under various conditions, on the range of results of these numerical predictions, and on their agreement with *in vitro* values. Concerns also exist when attempting to validate predictions with *in vivo* data under complex combined loading modes (*e.g.* compression and bending). To address these issues, one may compare the salient predictions of peer-reviewed models obtained under nearly identical loading and boundary conditions. For this purpose and due to the importance and complexity of the lumbar spine, this novel multicenter study was undertaken to compare the results of eight well-established FE models of the lumbar spine that have been developed, validated and applied for many years in different research centers around the globe. Tasks simulated consist of pure and combined bending, torsion and compression loads in order to better compare model predictions with each other and with the published *in vitro* and *in vivo* data. The objective is to evaluate the predictive power of individual estimations *versus* the median of all estimations. It is hypothesized that the median predictions of FE models when combined could more closely approximate the experimental data than the predictions of individual models.

2. Materials and methods

2.1. Inclusion criteria

Ten different research groups, working in the field of spinal FE modeling were invited to participate in the present study. Only validated models of the lumbar spine (L1-5) that were previously published in peer reviewed journals were considered. A model was considered to be validated when its predictions compared favorably with available measurements under simple loading conditions. From ten groups, eight agreed to participate, one declined due to lack of resources and one did not respond to the invitation. In the current study, complex combined loading modes were employed, for which not all models were validated previously. Thus, all results of the present study were anonymized to increase the number of participating groups. Only the first author (M.D.) had access to the non-anonymized data, and all research groups agreed to the current publication. The models were arbitrarily numbered from 1 to 8.

2.2. Study design

The first part of this study served as an *in vitro* validation attempt. Here, FE models were subjected to pure moments and pure compression under standardized loads recommended in experimental studies (Wilke et al., 1998). Results were compared with previously published *in vitro* values (Brinckmann and Grootenboer, 1991; Rohlmann et al., 2001b; Wilson et al., 2006). The second part served as a validation for the simulation of physiological movements of maximal voluntary motions in different planes. Therefore, previously published loading recommendations were employed, and the results were compared with available *in vivo* data (Pearcy, 1985; Pearcy et al., 1984; Pearcy and Tibrewal, 1984; Wilke et al., 2001) in which subjects were requested to perform maximal motions.

2.3. Finite element models of the intact lumbar spine

All osseoligamentous FE models employed in this study included at least five lumbar vertebrae and four intervertebral discs (L1-5, Fig. 1). FE models simulated the intact lumbar spine under static loading conditions. Detailed information about