DEVELOPMENT, IMPLEMENTATION AND APPLICATION OF A MULTI-BODY LUMBAR SPINE MODEL: TOWARDS A DETERMINATION OF THE ROLE OF SPINAL LIGAMENTS AND MUSCLES

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SUMMARY
For calculating physiological valid boundary conditions for more detailed spinal elements as well as perspective being able to understand and explain mechanical causes of low back pain and degenerative spine diseases, a multi-body model of the lumbar spine is developed. Ligaments and muscle-tendon-complexes are included and the model is controlled by physiologically motivated control theories.

As part of the modeling process, various spinal elements have to be formulated mathematically, thereby also defining the model’s level of abstraction.

The aim of this study is the derivation of a mathematical formulation for a non-linear spinal ligament. Other simulation results of ligament testing and modeling are used as a basis and experimental data from tensile tests on human spinal ligaments were used as input data.

After implementing the derived spinal ligament element in the underlying lumbar spine model, the evaluation of obtained simulation results allows for a more detailed estimation of the mechanical contribution of ligaments.

INTRODUCTION
Back pain is one of the major health problems, entailing major economic consequences. Degenerative spine diseases, e.g. degradation of the intervertebral discs (IVDs) and the vertebral bodies of the lumbar spine, are among them [1,2]. In vitro and in vivo measurements at the spine are supplemented by ‘in silico’ testing in order to gain a greater understanding of spinal behavior, to investigate spinal disorders and diseases and to biomechanically evaluate treatment options.

Concerning these computer simulation approaches, the multi-body simulation (MBS) and finite element method (FEM) are used for modeling purposes. On a smaller scale, FE models are used both for the calculation of internal stresses in vertebral bodies and IVDs, and on virtual prototyping and testing of spinal implants [3,4]. On a larger scale, MBS models of the full human or parts are often used to approach the issue of determining physiological boundary conditions for the FE models, as in-vivo measurements are extremely challenging [5].

The underlying project of the presented work is the development of a full human MBS model with a detailed lumbar spine including ligaments and muscles and controlled to perform movements by physiologically motivated control theories [6,7]. Internal forces and kinematics are calculated to be used as boundary conditions in more detailed FE models, e.g. of the IVD or spinal muscles.

For the development of the underlying full human MBS-model established model descriptions are used as a basis, while other elements, e.g. ligaments, muscles, need to be selected and adapted problem- and model-specifically.

In this study, the authors model-specifically decided how to model the relevant spinal elements, then developed and implemented a model function to describe the spinal ligaments as non-linear elements to be used in the underlying MBS-model of the lumbar spine.

METHODS
Various studies on spinal and ligaments in general concluded a non-linear behavior for ligaments, showing load-deformation curves with a sigmoid shape [8,9]. Furthermore, numerous ligament studies, mainly considering the knee, show the need for 3-dimensional ligament representation to be able to consider the experimentally measured non-uniform mechanical behavior [10,11]. However, so far spinal MBS-model often idealize ligaments as linear springs [12].

Figure 1: The force-length relation of the spinal ligament.

For the underlying lumbar spine model, we decided to model the relevant ligaments as non-linear straight-line elements, assuming the non-uniform mechanical behavior to be problem-specific negligible at this stage of the modeling process.
First of all, based on experimental results [8,9] showing the non-linear behavior of spinal ligaments, we assumed spinal ligaments to have a continuously differentiable transition between an initial non-linear region and a constant stiffness at higher loads (fig. 1). The well-known third, again non-linear portion, showing a concave behavior towards the tension axis was not taken into account, as the respective tensions will not be reached during normal or the movement to be simulated.

Analog to Günther et al. [13], who derived a mathematical formulation for the force acting on the serial elastic element of a Hill-type muscle, the force acting on a spinal ligament writes

$$F_{LIG}(l_{LIG}) = \begin{cases} 0 & l_{LIG} < l_{LIG,0} \\ K_{LIG,rel}(l_{LIG} - l_{LIG,0}) & l_{LIG,0} \leq l_{LIG} \leq l_{LIG,rel} \\ \Delta F_{LIG,rel} + K_{LIG,1}(l_{LIG} - l_{LIG,rel}) & l_{LIG} \geq l_{LIG,rel} \end{cases}$$

where \(l_{LIG}\) is the length of the spinal ligament. The relevant input parameters in ligament equation (1) are represented by

$$l_{LIG,0}, \Delta U_{LIG,0}, K_{LIG,rel}, \Delta U_{LIG,rel}, K_{LIG,1}$$

These were derived from four parameters: \(l_{LIG,0}\) (rest length of ligament), \(\Delta U_{LIG,0}\) (relative stretch at non-linear-linear transition), \(\Delta F_{LIG,0}\) (both force at transition and force increase in linear portion), and \(\Delta U_{LIG,1}\) (relative additional stretch in linear part providing the force increase \(\Delta F_{LIG,1}\), cf. fig. 1.

These four parameters, used as simulation input, in turn were derived using experimental data from tensile tests on 43 human spinal ligaments performed by Chazal et al. [8]. Their resulting load-deformation curves showed a sigmoidal shape, as used in our mathematical assumption. For four spinal ligaments, i.e. the anterior longitudinal (ALL) and posterior longitudinal ligament (PLL), the ligamentum flavum (LF) and in combination the supra and interspinal ligament (SSL/ISL), tension and elongation were estimated at transition (there named point A), at the end of the linear phase (point B) and the apex (point C) of the tension elongation curve. The mean values of the determined force and length data at A and B (table 1) were used to derive the ligament function’s input parameters, i.e. \(l_{LIG,0}, \Delta U_{LIG,0}, \Delta U_{LIG,1}\) and \(\Delta F_{LIG,0}\).

Additionally, each ligament’s rest length was calculated as the distance between two ligament’s attachment points after an inertial settling of the existing lumbar spine model and used as input \(l_{LIG,0}\). Attachment points for the four lumbar ligaments were defined in analogy to Panjabi et al. [9] and Pintar et al. [14]. Additionally, as proposed by Panjabi et al. [9], ligaments covering a wider spatial area, as the LF and SSL, were approximated by more than one pair of attachment points, i.e. multiple lines for one ligament. The calculated force (equation 1) was equally distributed. ALL, PLL and SSL were modeled by a single line.

### RESULTS AND DISCUSSION

On the basis of experimental data from tensile tests on human spinal ligaments, the authors show a mathematical formulation in order to model spinal ligaments with a non-linear behavior. The resulting force-length curves for ALL, PLL, LF and SSL show a good match with the experimental curves. The four ligaments, implemented as the new model element, were added to the underlying lumbar spine model, resulting in a more physiological description of the spinal ligaments. It remains open to complete new calculations, i.e. flexion-extension simulations, showing for example the influence of the spinal ligaments during stance.

### CONCLUSIONS

Having implemented the developed non-linear modeling element in the underlying lumbar spine model, the authors will include local and global muscle-tendon-complexes as modified Hill-type muscles [13] in a following step. This allows for a more detailed estimation of the mechanical contribution of ligaments, muscle-tendon-complexes as well as the already included intervertebral discs (as non-linear bushing elements).

### ACKNOWLEDGEMENTS

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### REFERENCES


### Table 1: Force and length at A, B, cf. Chazal et al. [9], used to derive the input parameters for the derived ligament function.

<table>
<thead>
<tr>
<th>Ligament type</th>
<th>Point A</th>
<th>Point B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Force (F_A) [N]</td>
<td>Length (l_A) [mm]</td>
</tr>
<tr>
<td>ALL</td>
<td>55</td>
<td>1,52</td>
</tr>
<tr>
<td>PLL</td>
<td>48,33</td>
<td>0,92</td>
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<tr>
<td>LF</td>
<td>75</td>
<td>1,6</td>
</tr>
<tr>
<td>SSL/ISL</td>
<td>40,14</td>
<td>1,54</td>
</tr>
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</table>