Sensitivity analysis of intervertebral disc parameters – MBS model of the lumbar spine

Sabine Bauer, Eva Keller, Dietrich Paulus

***Abstract*— The range of possibilities to investigate the biomechanical behavior of human biological structures is manifold. The classical investigation methods such as e.g. experimental studies and image processing are complemented by the biomechanical computer modeling. These different investigation methods represent their own fields of research, but a comparison of the results can be used to validate the applied method. Also explored material properties of different structures can be used, for example in the computer modeling, as input parameters. In order to ensure a realistic modeling, the knowledge of the influence of the structure-specific parameters on the biomechanical behavior of the entire model system is required. Especially the biomechanics of the intervertebral discs is seen in the literature as a central component of a spine model. Therefore, a detailed analysis of the impact of an input parameter variation is necessary. By means of a multibody simulation (MBS) model of the human lumbar spine, the impact of modified disc stiffness onto the spinal structures has been investigated. The used stiffness values are obtained from published literature. The model takes the biomechanical properties of the spinal structures such as the intervertebral discs, the fact joint and the ligamental structures into account and has been validated by comparing the results with results from appropriate literature. To analyze the effects of different input parameters variations on the biomechanical behavior of spinal structures, the upright standing is simulated.**

This research project shows that the implementation of different input parameters don't necessarily lead to massive changes of the biomechanical behavior of the structures in which the input parameter has been varied, but may have a greater influence on other modeled structures.

***Index Terms*— sensitivity analysis, intervertebral disc, MBS model, lumbar spine.**

I. INTRODUCTION

There are different approaches to identify spinal disorders: For example, medical imaging, experimental investigations or computer modeling. The most common medical imaging procedures are MRI and CT- imaging [1], [2], [3], [4]. With the help of these imaging techniques damages of soft tissue can be diagnosed and the bone constitution can be assessed. Another approach to identify spinal disorders is the experimental investigation. In in vivo studies a pressure sensor is inserted in a selected disc of a living person, so that the intradiscal pressure can be measured [5], [6], [7], [8]. In in vitro studies the kinematic quantities influenced by external forces or torques of autopsy can be determined [9], [10], [11]. A further method to identify spinal disorders is computer modelling. It is distinguished between the multibody simulation (MBS) modeling and finite element (FE) modeling. Each body of a FE model is divided into smaller sub-units. For each element the node displacement and the related change in tension is calculated by taking the specific material laws into account [12]. However, one disadvantage of FE modeling is the required computational time of the system, which is relatively long. According to Berkley [13] the models' accuracy increases with the number of finite elements that are used to describe the geometry. But each additional element also means an additional computational time. Chomphan [14] and Zhang [15] confirm that solving large numbers of FE equations leads to an enormously time-consuming calculation. The accuracy of the system and the expected computing time must therefore be carefully matched. A much faster method is the MBS. In MBS modeling the bony structures of the vertebral bodies are assumed to be rigid and thus not deformable. The individual bodies are linked through massless joints or force elements [16]. The acting external force activates the kinematics of the model, which is defined as a system of coupled differential equations. By numerical integration the kinematic variables, the transmitted forces and the torques are calculated.

One difficulty in modeling is that the input parameters, which are partly based on data from already published literature, may differ from one to the next publication. For example, the values for the stiffness of the intervertebral discs are dissimilar in the publication of Lavaste [17].

Due to the short computation time of MBS modeling, it is possible to analyze the impact of different input parameters on a broad spectrum of possible variations. This study investigates in which way the results depend on the input data that are used to define the material properties of the model. The effects of variations in the intervertebral disc material properties and the consequences on the spinal structures are analyzed.

II. MULTIBODY SIMULATION MODEL OF THE LUMBAR SPINE

A. *Surface generation and alignment of the lumbar spine model*

The vertebral surfaces of this model are based on CT-images of artificial vertebrae, whose size correspond to the average size of the vertebrae of Europeans. Plugins are developed to segment and to visualize the data sets (Fig. 1) and make them available for simulation [18], [19].

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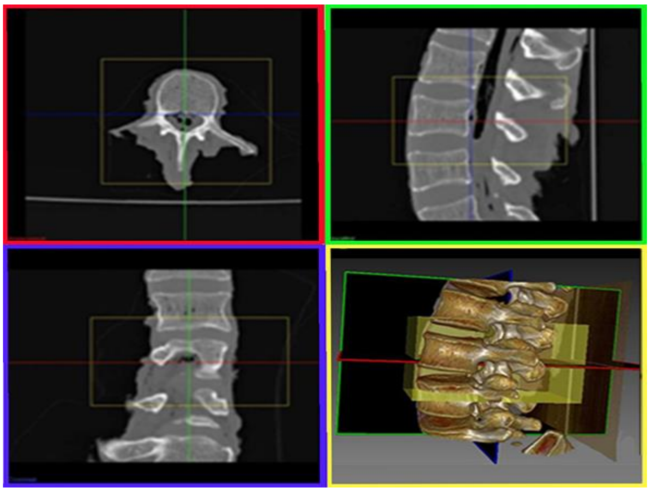

Fig. 1 Example for a segmented and visualized data set using self-developed plugins

The vertebral bodies are arranged so that the spinal alignment fulfills the characteristics of a well-balanced spine according to Roussouly [20]. All the conditions of a well-balanced spine are fulfilled in this model: the sacral slope is between 35° und 45°, the apex of the lumbar lordosis is located at the center of the L4 vertebral body, the lower lordosis is more prominent, the inflexion point is located at the thoracolumbar junction, an average of four vertebral bodies constitutes the arc of lordosis, and the average global lordosis angle is 61°.

B. Spinal structures: biomechanical properties

The lumbar MBS model (Fig. 2) consists of vertebrae L1-L5, the os sacrum, and the os ilium. The rigid bodies are connected by joints that are located in the middle between two vertebral bodies. At this point the forces and torques can be transmitted. The disc force is calculated by an equation, which is composed of a geometry-based stiffness and a damping term (1). The geometry-based stiffness term is composed of the stiffness c, the cross-sectional area CSA as a unitless factor and the deformation of the intervertebral discs Δr. The unitless factor CSA is included in the stiffness term to take the effects of the different disc sizes onto the disc properties into account. The damping term depends on the damping d and the velocity Δr'.

$$F = c \cdot CSA \cdot \Delta r + d \cdot \Delta r' \qquad (1)$$

The transmission of torques is based on experimentally determined curves for all three motion axes [21].

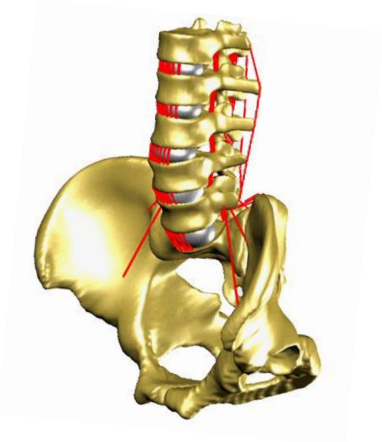

Fig. 2 MBS-model of the lumbar spine

Furthermore, the ligaments lig. longitudinale posterius (PLL), lig. longitudinale anterius (ALL), lig. flavum (LF) and lig. interspinale (ISL) as well as the lig. supraspinale (SSL) and the lig. intertransversarium (ITL) and ligg. iliolumbale are implemented in the model. A ligament is spanned between to marker points. As a ligament can only be defined between two points in the simulation, broad ligament structures are realized by a bundle of several fibres. The mechanical behaviour of the ligaments is also based on characteristic curves, which describe the force-deformation-relation of the individual ligaments [22].

In addition ten facet joints are included with a contact modeling. If the two corresponding facet joint surfaces are in contact, a force is developed in opposite direction of the movement (2).

$$\begin{pmatrix} F_y \\ F_y \\ F_y \\ F_x \\ F_z \end{pmatrix} = \begin{Bmatrix} c_y \cdot \Delta r + d_y \cdot \Delta r' : & c_y < 0;\ \Delta r < 0;\ \Delta r' < 0 \\ c_y \cdot \Delta r : & c_y < 0;\ \Delta r < 0;\ \Delta r' > 0 \\ 0 : & c_y < 0;\ \Delta r > 0; \\ 0 & \\ 0 & \end{Bmatrix} \qquad (2)$$

A more detailed description of the biomechanical properties of the structure can be taken from [26].

C. Validation of the model

The model validation was performed by comparing the simulation results with FE results and in vivo data from the literature [23], [24], [25], [26]. As an example, the pressure of the intervertebral discs of the each functional spine unit (FSU) is shown in Fig. 3.

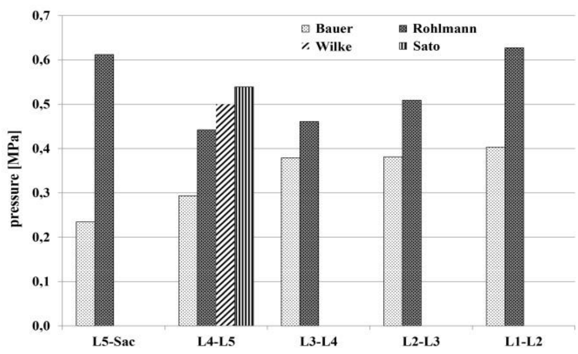

Fig. 3 Intervertebral disc pressure in comparison

Comparing the intervertebral pressure of the FSUs, it can be seen that the values are not exactly in the same order concerning magnitude. Particularly obvious are the differences in the results for pressure in the FSUs L5-Sac via MBS modeling (Bauer) and the finite element modeling (Rohlmann).

The rotational behavior of the discs and the loads of the facet joints are also validated with corresponding results from literature. A detailed description of the validation process and relevant conclusions about possible causes of discrepancies in results are shown in [22].

III. Realization of the Disc Parameter Variation

As already mentioned, different biomechanical parameters for the intervertebral disc stiffness can be found in literature. After the implementation of the different values, its effects on the spinal structures are examined. Lavaste [17] specifies his experimental obtained stiffness value c with $c=8*10^8$ N/m, his modeled stiffness value with $c=9*10^8$ N/m and indicates further stiffness values from experimental studies of other scientists with $c=10*10^8$ N/m (stiff_Lavaste_Markolf), $c=13*10^8$ N/m (stiff_Lavaste_Panjabi), $c=5.2*10^8$ N/m (stiff_Lavaste_Tencer).

To analyze the changes in the biomechanical behavior of the spinal structures, two series of studies are performed. In the first for all functional spinal units the same stiffness parameters are used. In the second study all possible combinations of the different stiffness parameters and all functional spinal units constitute the basic parameter configuration. With a total number of five different stiffness input parameters and five functional spinal units a possibility of 3125 combinations arises. For this number of combinations the loads of the intervertebral discs are calculated.

The most natural case, the upright position, was simulated as a load case. This means that an external force of 500N, which corresponds to the weight of the upper body, is applied in vertical direction on the top of the surface of vertebra L1. By this external force, the spinal structures are brought out of their equilibrium state before being transferred to a new one. This new equilibrium state is considered in the following results.

IV. Results

A. 1st study: same stiffness parameters for all FSUs

Considering the loads of the intervertebral discs, it can be seen that the forces in different FSUs are in a range between 400N and 500N (Fig. 4). In comparison the intervertebral discs of FSUs L5-Sac are loaded the lowest. The disc forces increase with in the subsequent FSUs. The largest force is developed in the intervertebral disc L2-L1. A possible reason could be the alignment of the vertebral bodies L2 and L1 and thus, the direction orientation of the force vector of the intervertebral disc L2-L1. In general, the smaller the inclination value of the intervertebral disc the higher the vertical component and the lower the horizontal component force of the intervertebral disc. In the presented MBS-model particularly the intervertebral disc of the FSU L2-L1 is slightly inclined so that the horizontal component of the intervertebral disc force is relatively small and the vertical force component correspondingly higher. A detailed explanation concerning the relationship between the alignment of the vertebrae and the force components can be seen in [22]. Within a FSU the reaction forces of the intervertebral disc are almost identical. Only small variation in disc forces can be reported in the FSUs L4-L5-L2-L3. The deviations are for this FSUs under 3%.

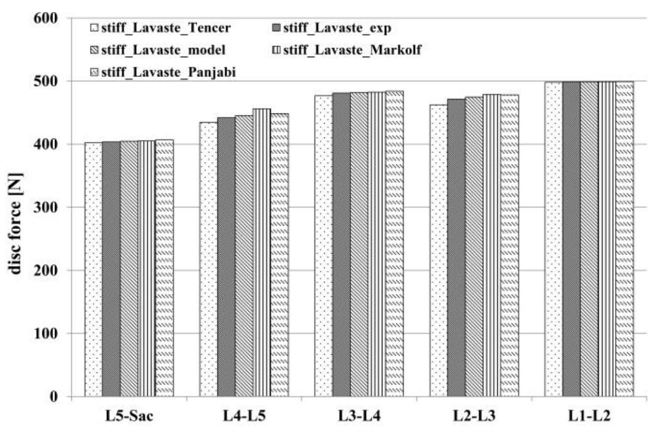

Fig. 4 Intervertebral disc force in comparison

The influence of different stiffness parameters on the extension and flexion movement of the intervertebral discs is nearly similar. Figure 5 shows on the x-axis the extension and flexion movement in degrees and on the y-axis the FSUs. The positive x-values describe the ventral directed flexion and negative x-values the dorsal directed extension movement. Within the individual FSUs the rotational directions are identical. But it should be noted that the simulated loading case, the upright standing position, generally causes only very small rotations. This is due to the fact that this modelled lumbar spine is "well-balanced" and thus, the alignment of the vertebrae is physiologically optimally. The comparison of the amounts of rotation of the individual FSUs with different stiffness parameters shows that the smaller stiffness value stiff_Lavaste_Tencer ($c=5.2*10^8$N/m) causes smaller rotation in the FSUs L5-Sac, L3-L4 and L2-L3 than using the higher stiffness value stiff_Lavaste_Panjabi ($c=13*10^8$N/m). The situation of the FSUs L4-L5 is exactly reversed. The higher stiffness parameters of Panjabi evoke larger rotations in these FSUs, than the stiffness parameters stiff_Lavaste_Tencer, stiff_Lavaste_exp, stiff_Lavaste_model and stiff_Lavaste_Markolf. The largest deviations, 26%, can be found for the FSU L2-L3.

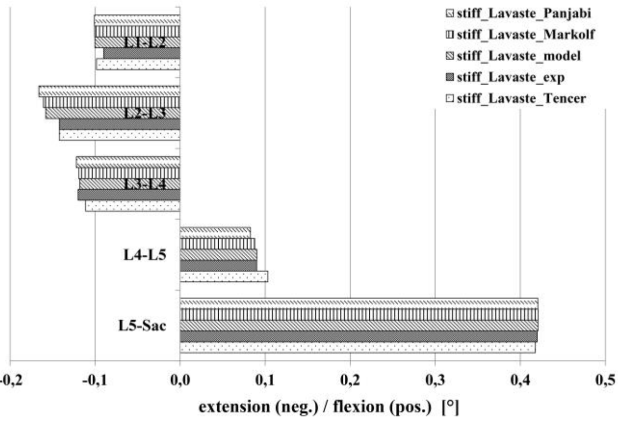

Fig. 5 Comparison of extension and flexion

Fig. 6 shows the loads of the facets joints of the FSU using different interdiscal stiffness parameters. In this load case, the corresponding facet surfaces touch and according to the equation (2) build an appropriate contact force. The reason, why only a very small force is built in the FSU L1-L2, is the alignment of the facet surfaces with respect to the acting external force. In particular, the facet surfaces of the FSU L1-L2 are aligned in parallel to the line of action of the external force so that the two surfaces slide past each other and have only little contact. In this case, a very small contact force is build up. It is evident that for all FSUs the facet force is higher when using small interdiscal stiffness parameters and larger when implementing higher stiffness parameters.

The stiffness has the biggest impact on the FSU L2-L3. In this FSU the smaller stiffness value stiff_Lavaste_Tencer also causes higher loads of the facet joints than the higher stiffness value stiff_Lavaste_Panjabi. This deviation can be justified by the above described characteristic of the rotations. For this FSU L2-L3 the extension has a direct impact on the loads of the facet joints. Due to higher backward tilting the posterior facet joints are more heavily loaded in this FSU.

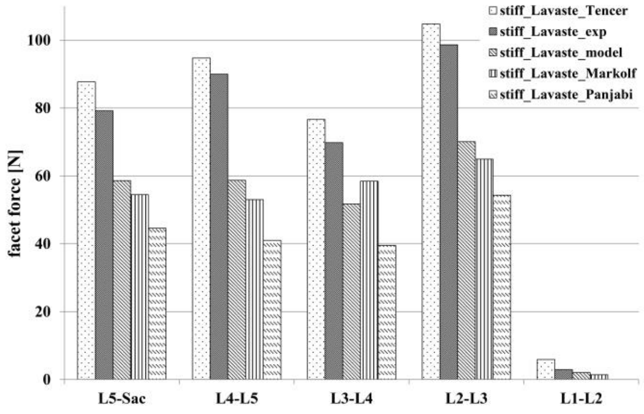

Fig. 6 Comparison of the facet loads

B. 2nd study: all possible combinations

The large amount of result data, which corresponds to a number of 3125 simulations, allows an even more intensive insight into the sensitivity of the model with respect to parameter variation. In this process the parameter configuration is determined in which the intervertebral discs of each FSU are loaded to the maximum (Table 1) and minimum (Table 2). In addition, the mean load of the intervertebral discs of each FSU and the standard deviation are calculated (Fig. 7).

Table 1 Maximum load of the intervertebral discs

	max. F_{disc} [N]	stiffness parameter configuration of the different FSUs				
		L5-Sac [N/m]	L4-L5 [N/m]	L3-L4 [N/m]	L2-L3 [N/m]	L1-L2 [N/m]
L5-Sac	435,6	$10 \cdot 10^8$	$9 \cdot 10^8$	$8 \cdot 10^8$	$10 \cdot 10^8$	$9 \cdot 10^8$
L4-L5	462,9	$10 \cdot 10^8$	$9 \cdot 10^8$	$8 \cdot 10^8$	$10 \cdot 10^8$	$9 \cdot 10^8$
L3-L4	495,0	$10 \cdot 10^8$	$13 \cdot 10^8$	$10 \cdot 10^8$	$10 \cdot 10^8$	$5{,}2 \cdot 10^8$
L2-L3	487,6	$10 \cdot 10^8$	$9 \cdot 10^8$	$8 \cdot 10^8$	$10 \cdot 10^8$	$9 \cdot 10^8$
L1-L2	499,7	$9 \cdot 10^8$	$8 \cdot 10^8$	$10 \cdot 10^8$	$8 \cdot 10^8$	$10 \cdot 10^8$

Comparing the maximum loads of the intervertebral discs with those who were reached by the parameter configuration in Fig. 4, it can be seen that the load of the FSUs are nearly equal.

Table 2 Minimum load of the intervertebral discs

	min. F_{disc} [N]	stiffness parameter configuration of the different FSUs				
		L5-Sac [N/m]	L4-L5 [N/m]	L3-L4 [N/m]	L2-L3 [N/m]	L1-L2 [N/m]
L5-Sac	266,0	$9 \cdot 10^8$	$13 \cdot 10^8$	$13 \cdot 10^8$	$5{,}2 \cdot 10^8$	$10 \cdot 10^8$
L4-L5	299,6	$9 \cdot 10^8$	$8 \cdot 10^8$	$13 \cdot 10^8$	$5{,}2 \cdot 10^8$	$5{,}2 \cdot 10^8$
L3-L4	345,7	$9 \cdot 10^8$	$8 \cdot 10^8$	$13 \cdot 10^8$	$5{,}2 \cdot 10^8$	$5{,}2 \cdot 10^8$
L2-L3	335,8	$10 \cdot 10^8$	$8 \cdot 10^8$	$13 \cdot 10^8$	$5{,}2 \cdot 10^8$	$5{,}2 \cdot 10^8$
L1-L2	455,9	$9 \cdot 10^8$	$13 \cdot 10^8$	$13 \cdot 10^8$	$5{,}2 \cdot 10^8$	$10 \cdot 10^8$

By contrast, highly different is the variance between the maximum values and the minimum values of Table 1 and Table 2. For example, the difference of the disc loading of the FSU L5-Sac lies at 169N, which corresponds to a 39% increase of the intervertebral disc loading. Conversely, this means if selecting the parameter configuration of the case "minimum load situation", small values are calculated for the disc forces, but this does not necessarily have to be correct. This example shows that, depending on the choice of parameters configuration, the input parameter stiffness can still strongly influence the load situation of the intervertebral discs.

The mean values of the intervertebral disc force, calculated from the 3125 parameter combinations, and the corresponding standard deviation are shown in Fig. 7. The standard deviation of the intervertebral disc forces is calculated as follows

$$SD = \frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{(n)} \qquad (3)$$

with x_i the i-th element of the sample, $\bar{x}$ the mean value and n the numbers of values.

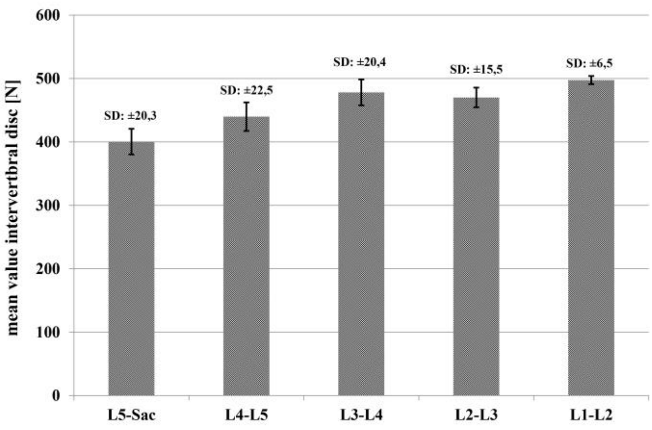

Fig. 7 Mean values and standard deviation

V. CONCLUSION

This study investigating the influence of the intervertebral disc stiffness parameter on the biomechanical behavior of the lumbar spine shows that some structures are less sensitive to changes of the intervertebral disc stiffness than others, such as the facet joints. As shown above, within each FSUs the facet joints are more than twice as heavily loaded. These significant differences in the facet loads, which have been purely caused by the variation of the intervertebral discs stiffness, underline that the modeling results largely dependent of the input parameters.

Although, according to Fagan [28], the intervertebral disc is the most critical component in most finite element models of the spine and its representation in the models therefore of great importance, it is also essential to evaluate the parameter influence of further spinal structures. Therefore, in a further study, we will investigate the influence of different characteristic curves of the ligaments, which are found in the literature.

In conclusion, the characteristics of the individual spinal structures cannot be considered in isolation, but the biomechanical behavior of certain structures can influence other structures. Currently the presented biomechanical behavior of the intervertebral disc is defined by a force law, which can be understood as an initial approach. To precise the biomechanical properties of the intervertebral disc a 3D hybrid model consisting MBS and FE units will be build. Lastly, it should be noted that, after further sensitivity analyses, we target patient-specific preoperative simulations to predict the effects on spinal fusion in overweighed and obese patients and to identify the best possible surgical option.

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