Analysis of the Biomechanical Effects of Spinal Fusion to Adjacent Vertebral Segments of the Lumbar Spine using Multi Body Simulation

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***Abstract*— Extensive mechanical loads on the lumbar spine often lead to degenerative damages of spinal structures. In many cases surgical interventions, such as spinal fusion, are unavoidable. An appropriate method for the estimation of the mechanical effects of such interventions to adjacent vertebral segments is the mathematical computer simulation. This paper presents a 3D-MultiBodySimulation- (MBS-) model of the lumbar spine with realistic surfaces of vertebrae and correct positioning relative to each other which is based on computer tomography (CT) measurements and segmentation processes. Intersegmental discs as well as ligament structures are included. For these elements the physical behavior like force-deformation relations and characteristic curves for the torque-angle relations are formulated. The facet joints are modeled as cartilage, in order to simulate the contact between the corresponding articular surfaces. With this model the loads on the different structures, before and after spinal fusion of the functional spine unit L5-L4, are calculated to show the biomechanical effects to adjacent vertebral segments under different load cases. The comparison of the simulations shows a redistribution of loads within the spinal structures. In the simulation case of spinal fusion, the posterior structures are more loaded than in the simulated healthy state. The validation of the model was carried out by comparing the results with FE-simulations, various in vitro experiments and experimental data from biomedical literature.**

Keywords- MBS mode; mathematical computer simulation; spinal fusion; adjacend vertebral segment loading

I. INTRODUCTION

Back pain is nowadays a prevalent disease and 70 to 85% of the population is affected by back pain during their lives [1]. The result is an increase in the number of spinal operations. The study [2] shows that the number of spinal fusions has increased to 220% within the years 2004 to 2009. But the use of such rigid implants, in which one or more motion segments are fully fused, is controversial. While it is seen by some as a recognized procedure, others doubt its effectiveness due to negative consequences for the adjacent segments [3], [4], [5], [6] [7]. The results of the FE studies of Rohlmann et al. [8] [9] shows that the implementation of an internal fixation device has only a small influence on the tension and intervertebral disc pressure.

The aim of our study was to develop a MBS model of the lumbar spine to calculate the forces and torques occurring in the different structures and to determine the resulting kinematics in case of spinal fusion and during the simulation of the healthy state under various load cases. Because in our case the load calculation is associated with very short computation times and surgical planning is increasingly performed computerized, in a further step our aim is to simulate the effects of such vertebral fusions preoperatively.

II. STRUCTURE OF THE MBS MODEL

The MBS model of the lumbar spine consists of the vertebrae L1-L5, the os sacrum and the os ilium. The vertebrae are connected by joints with appropriate degrees of freedom. The ligamentous structures are also realized as elastic elements. The facet joints are realized as 3D- contact areas, so that the acting contact forces avoid the penetration of two corresponding joint surfaces. All the individual structures are modeled with different material properties in order to simulate their realistic mechanical behavior [Figure 1].

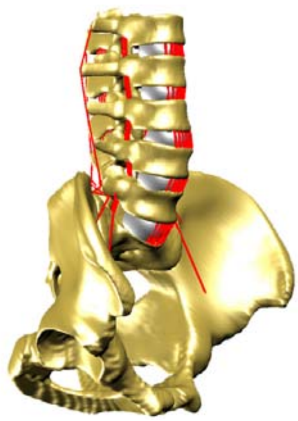

Figure 1. MBS model of the lumbar spine

A. *Generation of vertbral surface*

The CAD (Computer Aided Design) models of the individual body surface were obtained by segmentation of images of a computed tomography (CT). The templates of the body surfaces are artificial vertebrae, which represent the average size of an European. For segmentation and visualization of the DICOM data, a plug-in was developed [10], [11] to allow an individual processing of the CT data. By means of an algorithm for mesh smoothing and polygon reduction the amount of data can be varied [Figure 2], so that after the implementation of the surfaces in the MBS model a fast calculation time is guaranteed.

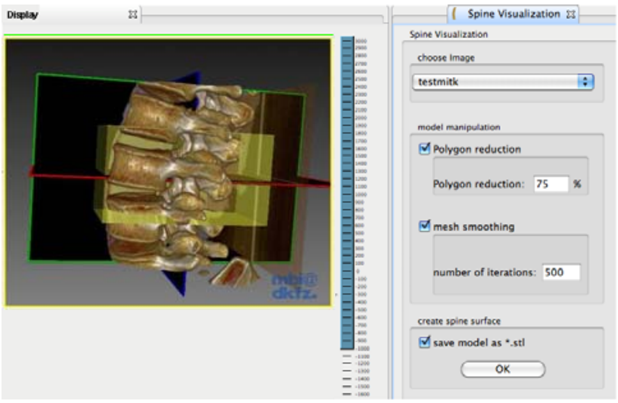

Figure 2. Plugin for a patient-specific visualization of the surface structures of vertebral bodies.

The positioning of the vertebral bodies follows the criterion that the endplates of the corresponding vertebral bodies superimpose in lateral direction and in sagittal direction. A further criterion is that the tilt angle of L3 is zero. Furthermore, the articular surfaces of the facets are oriented in such a way that the function of the joint is ensured.

B. *Modeling of intervertebral disc*

The intervertebral disc connects two adjacent vertebral bodies and is defined by six degrees of freedom, which distinction is made among the three components of force F_x, F_y and F_z and three components of torque M_α, M_β, and M_γ. The mechanical behavior of force, deformation and deformation velocity is described by the relation

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

with the parameter for stiffness c, the cross section area (CSA) and the deformation Δr. Also the parameter for the damping d and the deformation velocity Δr' are taken into account. The stiffness and damping parameters for the axial compression and the shear behavior are taken from literature [12], [13]. Following the idea of [14], allows the cross sectional area of the intervertebral disc describing a scaling factor for the respective functional spine units (FSU) of the lumbar spine. The mechanical behavior during intersegmental rotations is implemented by characteristic curves for each direction. They are calculated following the results of experimental measurements of isolated postmortem disc material [12], [23]. In Fig. 3 the characteristic curves of the disc L3-L2 during flexion and extension, lateral bending, and axial rotation are shown.

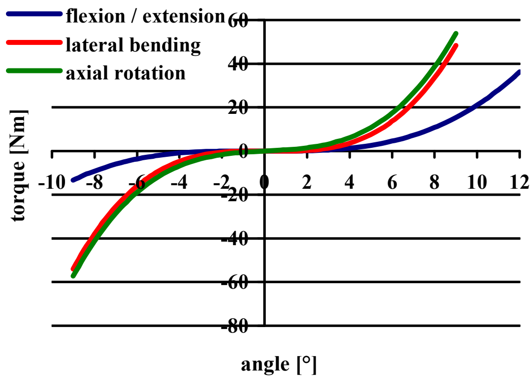

Figure 3. Characteristic curve torque-angle L3-L2.

C. *Realization of ligamentous strucutures*

The several vertebral bodies are not only connected by intervertebral discs but also by surrounding ligaments. The model of the lumbar spine includes, in every functional spine unit, 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 [Figure 4].

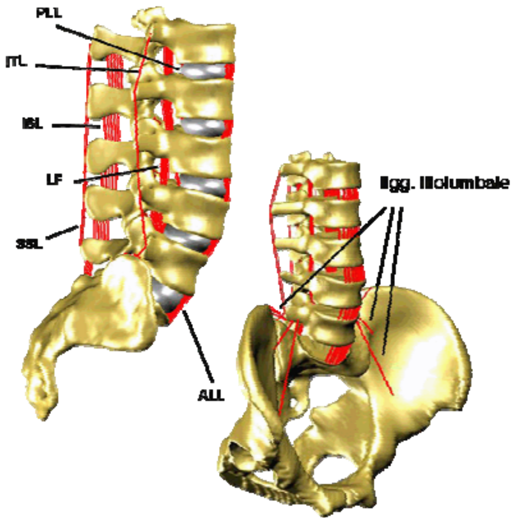

Figure 4. Ligamentous structures in the MBS-model of the lumbar spine.

All ligaments have a characteristic initial length. If ligaments are stretched due to movement of the vertebrae they produce a reaction force corresponding to the extension Δl following a specific characteristic curves [15].

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D. *Modeling of the facet joints*

The contact between the bony parts is realized by the facet joints. Every functional spine unit has a left and a right facet joint. The articular surfaces of these joints are implemented as 3D contact modeling. The contact force acting in normal direction between the corresponding surfaces counteracts the penetration of the surfaces during contact. For this contact force a rectangular range on the articular surface with an allowed depth of penetration is defined. In relation to the depth of penetration Δr and the velocity Δr' the following contact force is built

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

Where the parameters c_y and d_y are the constants for the terms of stiffness and damping.

E. *Modeling of the spinal fusion*

The above-described model with all the implemented biomechanical properties provides the basis configuration for the model with the fused intervertebral disc. To simulate a spinal fusion the model is varied so that between the vertebrae L4-L5 no residual movement is possible [Figure 5].

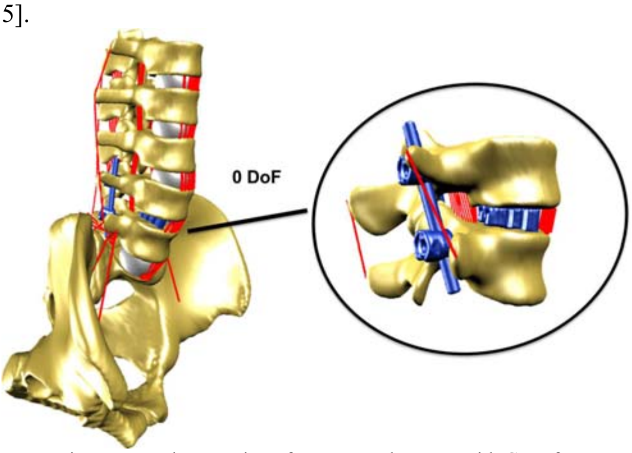

Figure 5. Implementation of a screw-rod system with Cage for simulating a spinal fusion.

In the following descriptions the model with no spinal fusion is called model 1 and the model with fused FSU L4-L5 is named model 2.

F. *Distribution of load in the lumbar spine*

To simulate the effects of an external force in the structures of the lumbar spine, an external force in the range of the weight of the upper body (G = 500 N) is applied in vertical direction on top of the surface of the vertebra L1. To investigate the effects of different load cases, the external force of 500N is gradually increased (100N) until it reaches an external force of 700N. In all load cases this external force causes small movements and the different structures in the models are out of balance, until a new equilibrium state is reached.

III. Results

A. *Kinematic and loads of model 1*

As a result of the simulation the curves of all forces and moments as well as the kinematic behavior of all different structures can be displayed. Example, the force curve and the torque curve of the spinal discs is shown at an applied force of 500N.

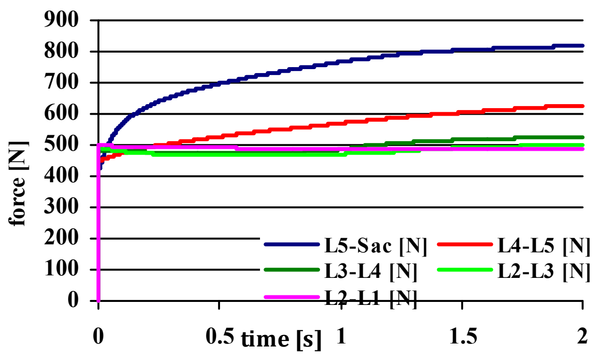

Figure 6. Reaction forces of the discs in vertical direction of the different functional units during an acting force of 500N.

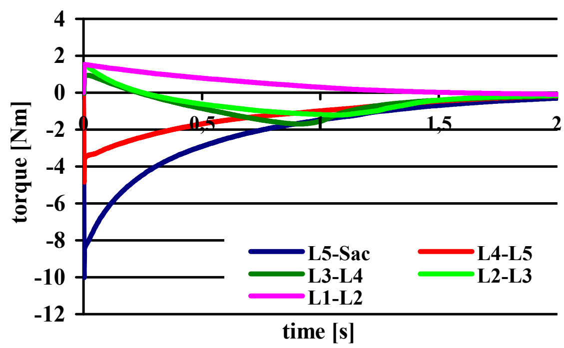

Figure 7. Torques in the intervertebral discs (flexion/extension) during an acting force of 500N.

The model is validated by comparing the calculated kinematic values with finite element modeling data and in vivo studies from literature [16], [17], [18], [19]. In figure 8 the pressure in the discs of the different functional spine units is shown. The results of the pressure in the functional spine units L5-Sac to L2-L3 are in the same order of magnitude. But the differences in the results of pressure in the functional units L2-L1 received by MBS modeling (Bauer_500N) comparing to FE modeling (Rohlmann) are obvious. The reason may be the use of different data for the cross section areas of the intervertebral disc L2-L1 in the several models.

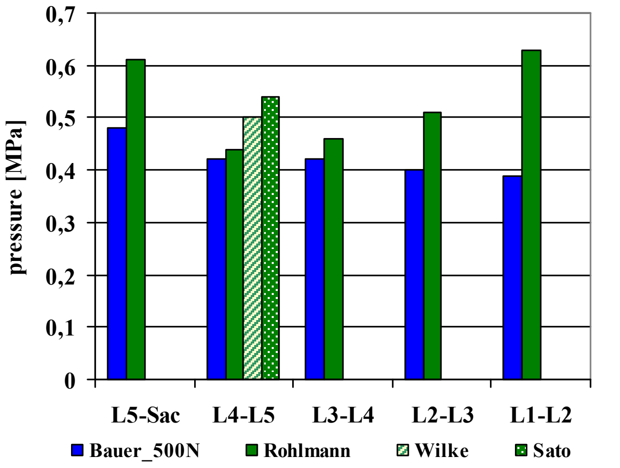

Figure 8. Comparison of the model simulation results with FE-Model and in vivo experiments of the disc pressure.

A far more conceivable reason can be the different directions of the intersegmental rotation of the discs [Figure 9]. While in the FE model Rohlmann all functional units perform, under the same external force, flexions, the highest FSU L1- L2 of the MBS model Bauer_500N performs an extension movement. As a result, the discs are relieved.

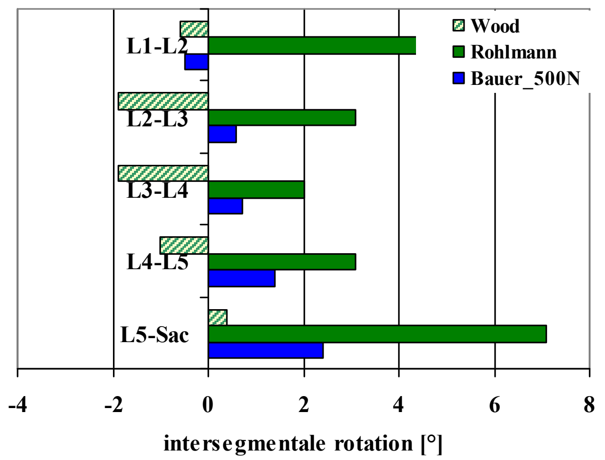

Figure 9. Comparison of the intersegmental rotation of the discs.

For a further validation of the MBS model a number of sensitivity analysis were performed to evaluate the sensitivity of the input parameters [20], [21], [12]. The intention was to identify parameters that influence the simulation results significantly even at small variations. As already described, three load cases were simulated using the MBS model. Based on the external load of 500N, the model was then loaded with 600N and 700N. With the increase of the external load the pressure of the intervertebral discs also increase (Figure 10). In comparison to the lower FSU the upper FSU are less loaded.

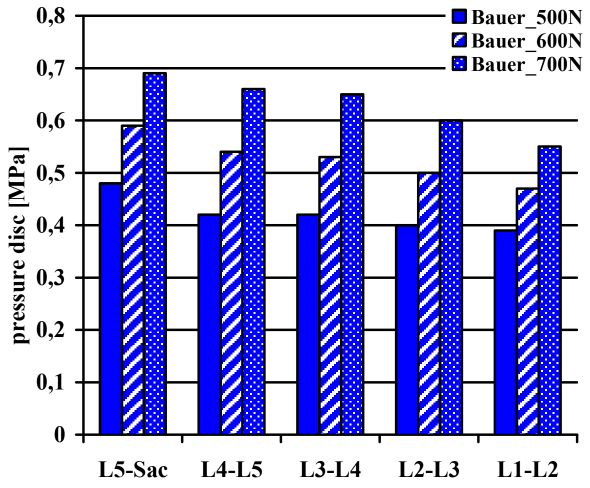

Figure 10. Comparison of the pressure in the discs of model 1 during different loads.

A almost similar load distribution is obtained when looking at the loads of facet joints (Figure 11). It can be seen that the facet joints of the FSU L1-L2, despite increasing external force, are less loaded.

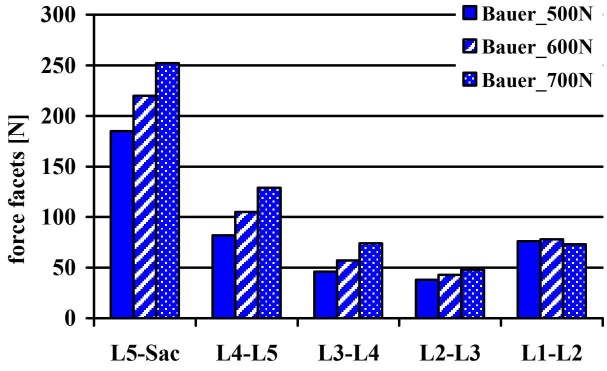

Figure 11. Force of facet joints of model 1 during different loads.

The reason for the relief of load in the ventral structures is the chance of direction of the intersegmental rotation (Figure 12).

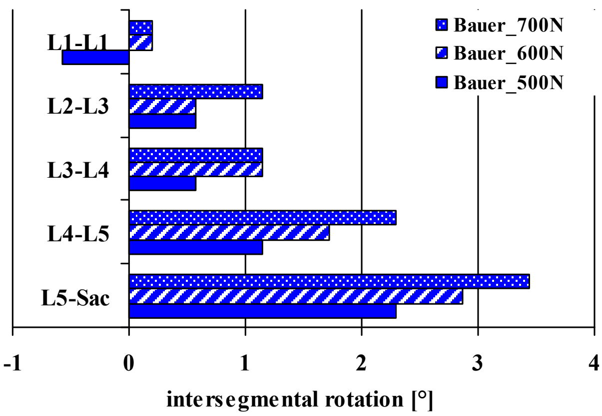

Figure 12. Intersegmental rotation of the FSU's under different loads.

B. *Effects of spinal fusion*

To simulate the effects of a spinal fusion of the FSU L4-L5 under different load cases, the mechanical properties of the MBS model were adjusted so that no residual movement in this FSU is possible. Thus two models of the lumbar spine were created.

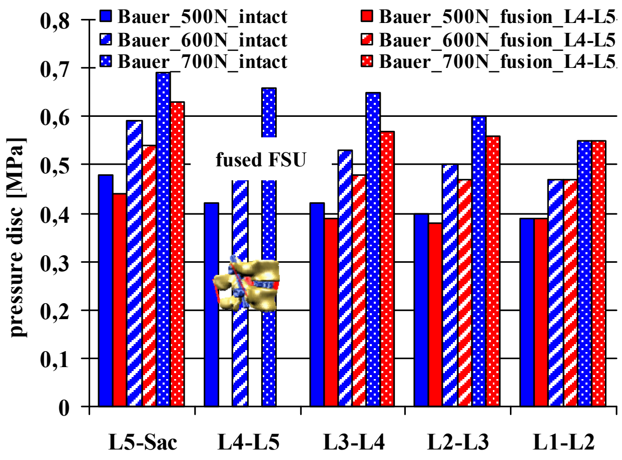

Figure 13. Comparison of the intradiscal pressure of model 1 and model 2 during differenet loads.

Considering initially only the bar graph of the disc force of the model without fusion, it can be seen that the pressures in all FSU increase with increasing external force (Figure 13) Comparing the pressure of the intervertebral discs of both models, the pressure in the FSU's L5-Sac to L2-L3 of the model with fused FSU L4-L5 are lower than without fusion. The disc loads of the FSU L1-L2 are almost the same.

The bar graph figure 14 shows the forces of the facet joints of the different functional units of both models in comparison. The figure clearly shows that after fusion the forces in the facet joints are particularly higher in the upper FSU.

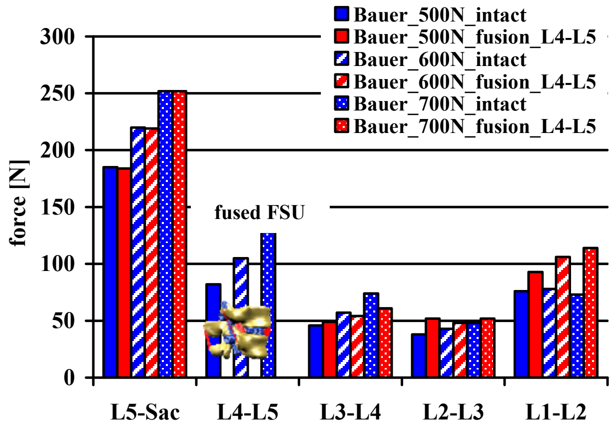

Figure 14. Comparison of the facet forces of model 1 and model 2 during differenet loads.

In figure 15 the intersegmental rotations of the discs are shown. When considering only the FSU angular position of the model with fused disc, it can be seen that while the intervertebral discs of all FSU perform flexion, the intervertebral disc of the FSU L1-L2 performs an extension movement. Comparing now the displacements of the discs with and without fused L4-L5 disc, it can be seen that the discs of the fused model perform less deflection.

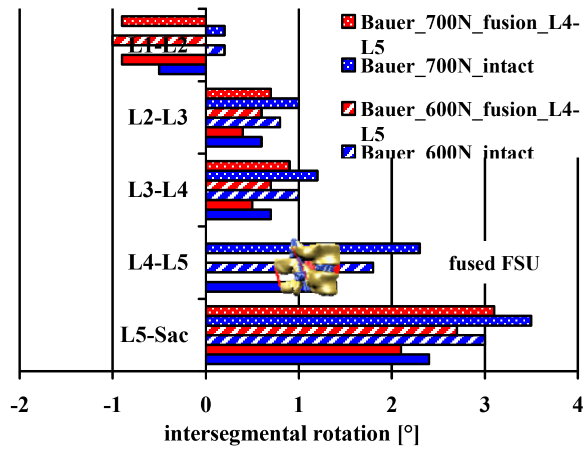

Figure 15. Comparison of the intersegmental rotation of model 1 and model 2 during differenet loads.

This change in direction of motion may cause a redistribution of loads in the different structures. In summary it can be stated that because of the fusion L4-L5 ventral lying structures such as intervertebral discs, are loaded less than posterior located structures.

IV. DISCUSSION AND CONCLUSION

In this research paper, a computer model was created to compute the load changes of the internal structures and the change of the kinematics during different external force applications in a model with and without fusion. This shows that MBS simulation is an appropriate method to determine the distribution of load for medical scenarios.

But of particular importance is the validation of a computer model. The quality of the computed results is only as good as the quality of the model creation allows. Only statements can be made within the modeled accuracy. For the validation results the difficulty of developing a suitable method, which confirm the accuracy of the modeling. An established method is comparing the obtained results with results from accepted publications. But it has to be mentioned that not always all parameters are published, which may have a significant influence on the result. For example, we showed in [22] that with variation of the spine curvature and keeping the input parameters constant, this has a significant effect on the load distribution of the spinal structures. Therefore, further parameters and studies are required.

Because the MBS load calculation is obliged with very short computation times and surgical planning is increasingly performed computer-based, in a further step a patient-specific preoperative simulations is sought to predict the effects of a spinal fusion and to identify the best possible surgical option.

Further in future a transfer of topographic and kinematic simulation data of implants in a 3D planning and navigation procedures is conceivable. In this process coordinates of the implants from the computer model and the 3D model data of the spine may be transferred in the appropriate data format to the navigation system.

Another advantage of this short computation times is that such an MBS model can be extended by further structures to get a more realistic simulation of the properties of the human body.

Figure 16. Integrated sub-model of the lumbar spine into a MBS model of the whole human body

The model of the lumbar spine presented in this paper can be integrated as a sub-model into a MBS model of the whole human body (Figure 16). Thus, conclusions about the load situations of the highly detailed modeled spinal structures during different simulations of human movements can be drawn.

Figure 17. MBS model of the whole human spine

Our next aim of our research is, to analyse the effects of different loads on the sagittal balance by extend the model of the lumbar spine to a model of the entire spine (Figure 17).

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