Multisegemntal fusion of the lumbar spine a curse or a blessing?

A MultiBodySimulation (MBS) modeling

Abstract: Excessive mechanical load of the spinal structures during unfavorable movements in daily life can lead to degenerative damages especially of the lumbar spine. If the affected structures are damaged in such a way that conventional therapy does not improve the situation, often a surgery is unavoidable. One surgical method is the fusion of the affected spinal segments. In particularly difficult cases, the fusion may even extend over more than one functional spinal unit. An appropriate method for the estimation of the biomechanical effects of such interventions to adjacent vertebral segments is the computer simulation. This paper presents a 3D-MultiBodySimulation- (MBS-) model of the lumbar spine with realistic surfaces and included intersegmental discs as well as ligamental structures. 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 simulation, the effects of mono- and multisegemntal fusions to the lumbar structures can be analyzed. The comparison of the simulations shows a redistribution of loads within the intervertebral discs. In the simulation case of monosegmental spinal fusion, the intervertebral disc below the fused segment 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 of vitro experiments and experimental data from biomedical literature.

Keywords: MBS model; monosegmental fusion; multisegemntal fusion; adjacent vertebral segment loading; load redistribution

1 Introduction

Back pain has become a widespread disease. 70 to 85% of the population is affected by back pain during their lives [1]. The suffering of many patients may be taken only by surgery. In the year 2004 to 2009, the number of spinal fusions has increased to 220%. But the use of such rigid implants, in which one or more motion segments are fully fused, is controversal. While it is seen by some as a recognized procedure, others doubt its effectiveness due to negative consequences for the adjacent segments [2–4]. The results of the FE study of Rohlmann et al. [5] 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 occurring in the different structures in case of mono- and multisegmental spinal fusion and during the simulation of the healthy state.

2 Structures 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 CAD (Computer Aided Design) models of the individual body surface were obtained by segmentation of images of a computed tomography (CT). A detailed explanation of the surface configuration can be taken out of [6]. The vertebrae are connected by joints with appropriate degrees of freedom. The ligamentous structures are implemented 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 these individual structures are modeled with different material properties in order to simulate their realistic mechanical behavior. A detailed description of all modeled spinal structures and used material properties can be taken from the publication [7]. The above described model with all the implemented biomechanical properties provides the basis con-
figuration for the model with fused intervertebral disc. To simulate a spinal fusion, the model is varied so that between the different vertebral bodies no residual movement is possible (Figure 1).

In this way eight cases were simulated: with monosegmental spinal fusions of different functional spine units FSUs (fusion L5-Sac, fusion L4-L5, fusion L3-L4, fusion L2-L3, fusion L1-L2), multisegmental fusion (fusion L5-L3 and fusion L5-L2) and a simulation with no fused discs.

2.1 Load distribution

An external force in the range of the weight of the upper body ($G \approx 500$ N based on [8]) is applied in vertical direction on top of the surface of vertebra L1. This external force causes small movements and the different structures in the models are out of balance, until a new equilibrium state is reached.

3 Validation

The validation of the MBS-results was performed by comparing the calculated kinematic values with finite element modelling data and in vivo studies from literature [8–11]. In Figure 2 the pressure in the discs of the different functional spine units is shown. In all functional spine units the pressure is almost in the same order of magnitude. Differences in results of pressure in the functional units received by MBS modeling (Bauer) comparing to FE modeling (Rohlmann) are given. In general the reason may be the use of different data for the cross section areas of the intervertebral disc in the several models. A force which is acting on a small cross-sectional area of a disc, leads to lower intervertebral pressure, than the same force acting on an intervertebral disc with a bigger cross-sectional area.

A far more conceivable reason can be the different directions of the intersegmental rotation of the discs (Figure 3). While in the FE model Rohlmann all FSUs perform, under the same external force, flexions, the FSU L3-L4, L2-L3 and L1-L2 of the MBS model Bauer performs an extension movement. As a result, the discs are relieved.

For a further validation of the MBS model a number of sensitivity analysis were performed to evaluate the sensitivity of the input parameters e.g. [12]. The intention was to identify parameters that influence the simulation results significantly even at small variations.
4 Results

4.1 Effects of monosegmental fusion

The following figures show the effects of the external load of 500 N without fused vertebrae in green and the yellow tones represent the impacts of monosegmental fusion.

While the vertebral segments of the model without fused discs perform only flexion, there will be a change in rotation in the models with fused vertebral segments. The vertebral segments perform, from functional spinal unit L3-L4, extension movements.

In general, the loads in the facet joints depends on the orientation of these facet joints in space according to the acting external force and further depends on the direction of rotation of the corresponding vertebral segments. In this model, the facet surfaces of the lower joints have a smaller inclination angle relative to the transverse plane, than the above localized facet surfaces. This has the consequence that the more likely vertical to the external force oriented facet surfaces are loaded higher in the model without fusion. In the upper segments the facets are oriented more parallel to the acting external force so that the facet surfaces rather slide past each other. Comparing the loads of the upper facet surfaces, of the models with fused vertebrae units with the model without fused vertebral segments, it can be seen clearly the high loads of these facets. One reason may be that changed direction of rotation of the vertebral bodies. By extension movement the corresponding surfaces of facet joints become more prominent in touch. Therefore, an increased reaction force is build up in the facets (Figure 5).

4.2 Effects of multisegmental fusion

The modeling of the multisegment fusions was realized by fusing two (L5-L3) or three (L5-L2) FSUs. The degrees of freedom were restricted, so that no movement is possible anymore.

Comparing the forces in the intervertebral discs, under the load of identical external force, it can be seen that a two or three-segmented fusion has no major impact on the adjacent discs. A very slight deviation resulting from the functional unit L5-Sac. In this unit, the discs of the models with multiple fused vertebral segments are slightly less loaded.

Similar changes of intervertebral rotations, like the monosegmental fusion, cause the multisegmental fusions. The intervertebral discs move from a flexion movement to an extension movement.
Figure 7: Forces of the intervertebral discs during no fusion and multisegmental fusion.

Figure 8: Intervertebral rotation during no and multisegmental fusion.

Figure 9: Forces of the facet joints during no and multisegmental fusion.

The multisegmental fusions have no significant impact on the loads of the intervertebral discs, but cause a disadvantageously redistribution of the upper spine located facet joints. Compared to the model with unfused vertebral discs, the upper facets are now significantly higher loaded (Figure 9).

5 Discussion and conclusion

A MultiBodySimulation was presented that enables to determine the load changes of the internal structures during the same external force application in a model without fusion, monosegmental and multisegmental fusion. As shown in paragraph 4.1 and 4.2, some structures are relieved by specific surgical fusions, but others are more loaded by these interventions. It can therefore be spoken of a redistribution of loads. 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. The modeling and the validation process is to be regarded as incomplete and will be advanced in future research. For example, the currently missing muscles will be implemented in the next modeling step.

Author’s Statement
Conflict of interest: Authors state no conflict of interest.

Material and Methods: Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use has been complied with all the relevant national regulations, institutional policies and in accordance the tenets of the Helsinki Declaration, and has been approved by the authors’ institutional review board or equivalent committee.

References


