A DEVELOPMENT PROCESS FOR CREATING FINITE-ELEMENT MODELS OF CRASH TEST DUMMIES BASED ON INVESTIGATIONS OF THE HARDWARE

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ABSTRACT

Crash test dummies act as a surrogate for humans in high loading conditions. Their anthropometry and properties have been retrieved in extensive research in the field of biomechanics. Accessibility to technical drawings and other specifications of crash test dummies is normally limited to their manufacturers. Furthermore, the hardware is affected by manufacturing tolerances, especially the complex shapes of dummies. Nevertheless reliable numerical simulation models are needed to support virtual engineering processes.

In order to build up a Finite-Element-Method (FEM) simulation model, a process was defined to retrieve all relevant data by investigation of the hardware. The BIORID-II dummy was chosen to demonstrate this process.

In a first step, it was necessary to capture the geometry of the BIORID-II. It is important to identify not only the exact geometry of every single part but also the assembly to know about the initial position. Different measuring methods such as optical 3D scanners, photographic analysis and manual measuring methods were used for this purpose. Based on these geometrical data FEM meshes were created.

In a next step, functional characteristics of subassemblies were analyzed by separate testing. In case of the BioRID II - Dummy, the behavior of different springs, dampers and cables were determined, especially the characteristic of the materials. In the spine of the dummy several pre-stressed elements made of hyper-elastic materials exist, therefore not only the behavior of the material but also the initial condition were important.

For validation purposes, three different tests have been used: the prescribed calibration test, an additional sled test, both with the torso only, and a sled test with a car seat and the whole dummy. The numerical simulations showed good accordance in comparison to both hardware tests and component tests. The calibration test was passed.

INTRODUCTION

According to the Economic Commission of Europe, about 14.9% of accidents in Europe are rear impacts [10].

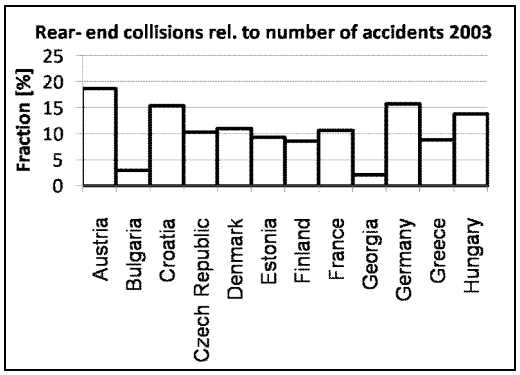

Figure 1: Fraction of rear-end collisions (1/2)

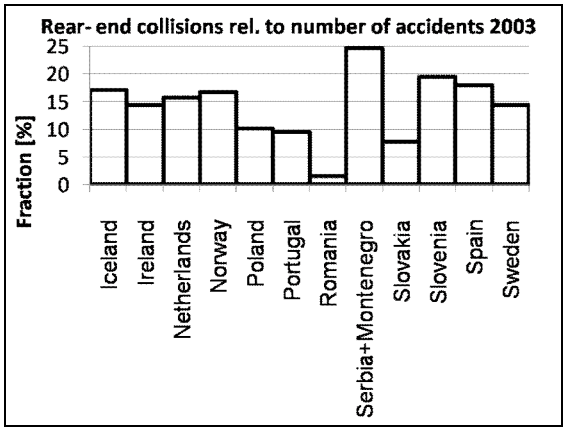

Figure 2: Fraction of rear-end collisions (2/2)

In Figure 1and Figure 2 the fraction of rear-end collisions relative to the number of accidents in different countries is shown.

Within these accidents, the risk for so-called Whiplash Associated Disorders (WAD) [8] is two times higher than in two- way traffic (see Figure 3 [9]).

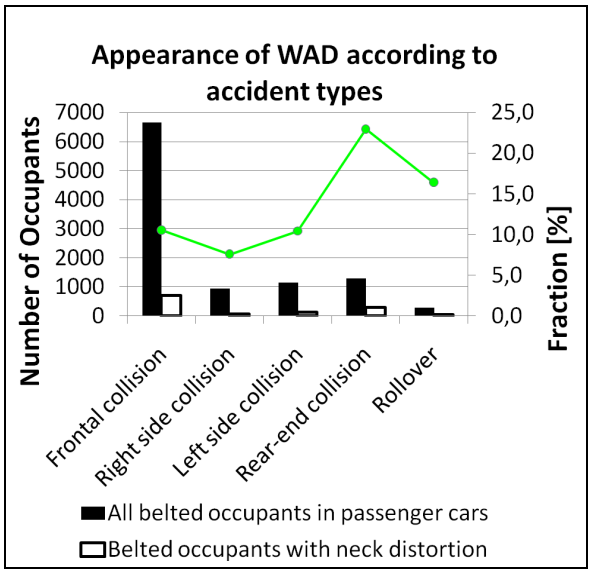

Figure 3: Appearance of Whiplash Associated Disorders according to accident types [9]
The black column shows the number of all involved belted occupants, the white column the number of involved belted occupants with a WAD injury. The solid line shows the fraction between these two numbers. WAD injuries are two times more frequent in rear end collisions compared to frontal and side collisions.

The injury mechanism has not been definitely clarified yet, and is still under investigation. Research in biomechanics, carried out by Chalmers University of Sweden and Denton ATD [2], has resulted in the development of the BioRID II dummy. This manikin reproduces the typical kinematics of a human being in a straight, two dimensional rear end collision. For development of systems for neck protection, dynamic testing (e.g. the new Euro-NCAP whiplash assessment) [7] is widely used by automotive industry. Yet, requirements of time-to-market and cost-efficient development processes also require numerical simulation models of the BioRID II.

The present paper describes a method how to build up a numerical FEM model based on investigation of the hardware. This approach was chosen for two reasons: First of all, technical drawings and other specifications of dummies are usually not obtainable outside of the manufacturing company. Secondly the properties of the hardware are affected by manufacturing tolerances.

The BioRID II dummy was used for demonstration of the process described here. It is based on the Hybrid III Dummy and modified in the following body regions [2] (see Figure 4):

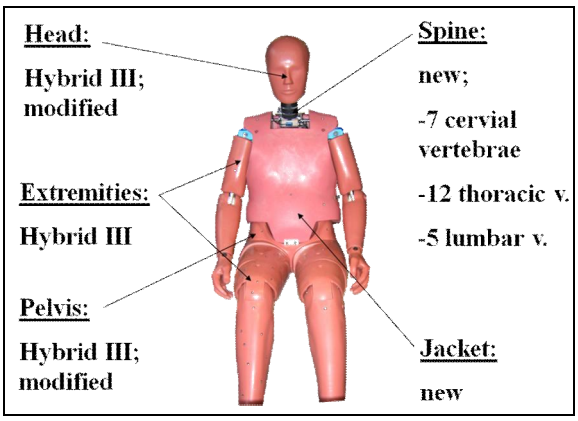

Figure 4: BioRID II Dummy, configuration [2]

The extremities were adopted from this dummy, torso and the head/neck region were redesigned: In the BioRID II a new articulated spine with 7 cervical, 12 thoracic and 5 lumbar vertebrae was implemented. The neck contains a pre-stressed system with cables, springs and dampers to reproduce the behavior of muscles. Cervical vertebrae made of rubber belong to this pre-stressed system. The silicon flesh of the torso contains a water filled bulb to represent soft tissue. Head and pelvis are based on the Hybrid-III design and were modified for connection to the new torso.

METHODOLOGY

For carrying out the investigation a hardware model of the BioRID II dummy was available. The proposed process can be described by a modified V-model approach, see Figure 5. It starts by disassembling the hardware into subsystems and components. All parts are modeled and simulated. Suitable experiments from component to system level provide data for verification of the model at all levels.

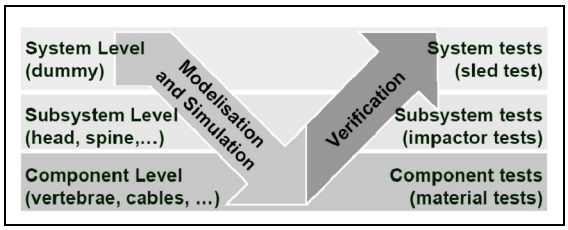

Figure 5: Working process (V-model approach)

Starting from the complete hardware, the dummy was modeled, simulated and verified at different levels of complexity (component, subsystem and system level)

The whole process is divided into five main steps:

- Capturing the geometries
- Translating geometries to CAD data
- Generation of the FEM meshes
- Development of the single components
- Validation of the model

Capturing the geometries

In a first step, the geometry of the dummy was digitized. Therefore both the surfaces of every single part and the shape of the assembled object were captured.

Most of the outer parts of the dummy are made of soft materials. So it was decided to use a contactless method for recording the outer shape of the whole dummy to avoid influences due to compression of single parts. An optical 3D scanner had been selected because of its fast mode of operation (see Figure 6).

Figure 6: Optical 3D-scanner Atos III (GOM)

To capture the parts, the dummy was disassembled completely. Every single part was examined to decide for the adequate method for capturing its geometry. Simple shapes like cylindrical bolts were measured by using manual procedures. More complex parts were digitized by using the 3D scanner (see Figure 7).

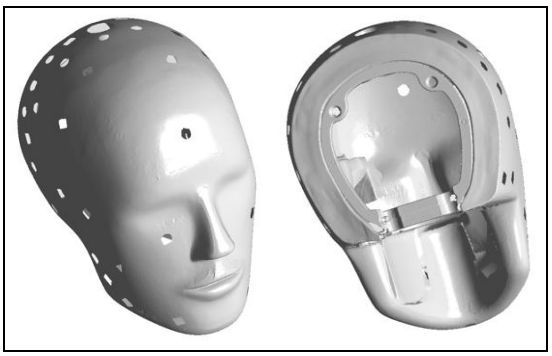

Figure 7: 3D- scan of the dummy head

The torso of the dummy presents the most complex component. It is too unstable to catch the whole part with the 3D scanner with a single scan. Therefore it was necessary to turn it around. That movement caused deformations and it was not possible to get consistent measurement data. To identify the outer geometry manual as well as scanner based methods were used in conjunction with geometrical matching concerning the attached parts. The internal parts like the water bulb were captured by using x-ray in combination with the above mentioned methods (see Figure 8).

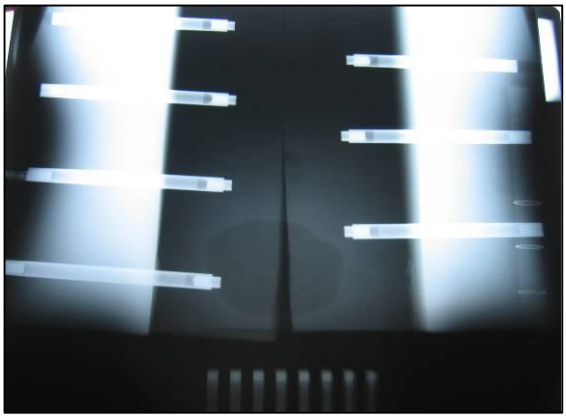

Figure 8: X- ray photograph of the torso

Translating geometries to CAD data

It appeared that the accuracy of the geometries provided by the 3D system was limited for creating FE meshes. Because of the complexity of the generated geometry it is intricate to use them as base for meshes. So the next step was to develop a CAD model based on the available geometrical data

Generation of the FEM meshes

The CAD data provided a suitable base for the meshing process and a complete FEM mesh of the dummy was built.

Again, the torso was the most challenging part for meshing. It was necessary to use 3D elements (solids) to represent it in the FE model (see Figure 9). Due to its complex shape automated meshing routines could not be used to build up the mesh so it had to be done manually.

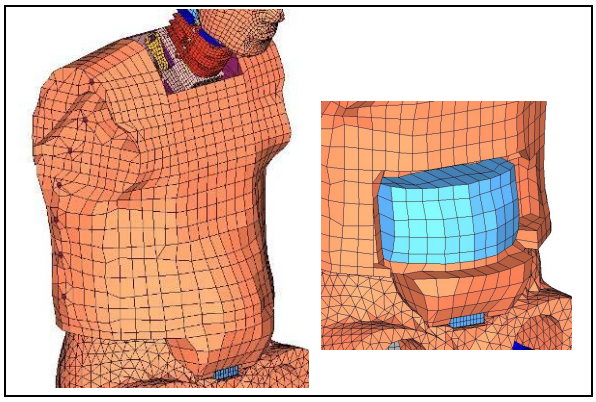

Figure 9: FEM-mesh of the torso

Development of the single components

To reproduce the behavior of the dummy in FEM simulation it was necessary to determine the characteristics of materials and its functional subassemblies.

First of all the material had been characterized. Therefore several hardware tests with the different materials like the silicon of torso and extremities and the bumpers at the spine were carried out: a pendulum was used to identify the dynamic behavior of the materials at different strain rates.

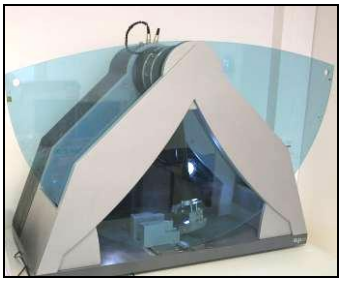

Figure 10: Pendulum for material tests from 4A (formerly A.P.E.)

For this reason defined material samples had been loaded dynamically by a pendulum. The deceleration of the pendulum was used for the determination of the material data (see Figure 10).

In a next step the components like the springs at the spine were tested concerning their behavior. Because of some known characteristics [4] it was agreed on skipping testing of the rotational damper.

Validation of the model

To validate the model on system level three tests were chosen:

- Denton calibration test [3]

  This test is prescribed to calibrate the hardware dummy within its designated loading conditions. The torso is mounted onto a rack without pelvis and extremities. A pendulum accelerates the rack according to a predefined acceleration pulse. Several dummy responses have to stay within prescribed corridors. Tests and simulations were performed according to the official calibration protocol data. [5].

- Sled tests with torso only

  These tests had been performed with a special defined configuration. It is similar to the Denton calibration test but an adjustable headrest is included. The acceleration was oriented at the trapezoid shaped pulse of the EuroNCAP procedure for seat tests [7].

- Sled tests with whole dummy and car seat

  To validate the behavior of the model in a realistic environment, testing data of sled tests were provided by the project partners. The tests included a whole dummy inside of a car seat.

RESULTS

The projectôs aim was to build up an accurate FEM model of dummies based on inspection of the hardware. The model should achieve the following defined criteria:

- The modelôs geometry in the model should fit to the hardware
- The components should reproduce the characteristics of the hardware
- The subsystems should reproduce the characteristics of the hardware
- The dynamic behavior of the whole model should reproduce the behavior of the hardware

Geometry

The overlay of captured geometry and mesh shows the accordance of single parts and assembly (see Figure 11).

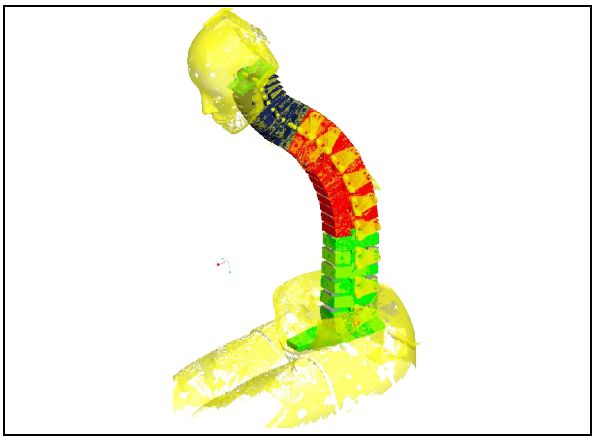

Figure 11: Accordance of CAD- Data (base of the mesh) and captured geometry
The transparent parts represent the captured geometry, the opaque parts are showing the FE mesh

Validation tests on component level

For material tests, original components were used to derive the properties of the FEM material model. Figure 12 shows the accordance between test and simulation by the example of the torso flesh material.

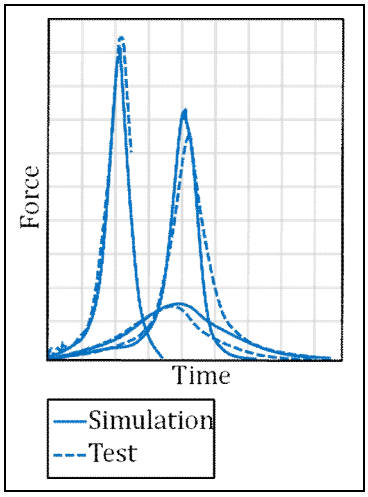

Figure 12: Accordance of simulation and test
The continuous lines show test results, the dotted lines show the according simulations

The behavior of the rotational damper- sub- model fits to the specified corridors (see Figure 13). The neck springs have been tested by static charging tests.

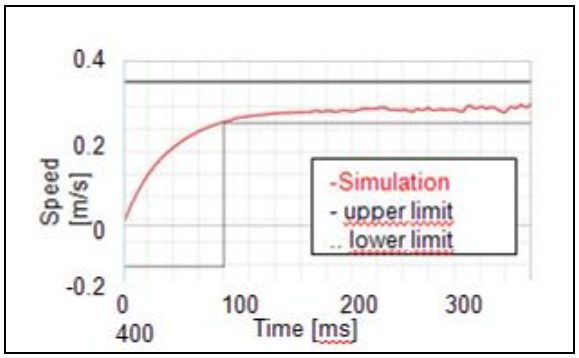

Figure 13: Characteristic of the rotational damper with 9kg- charging; limits according to [3]

Validation tests on subsystem level

In the present case study ñBioRID IIò it was essential to implement pre-stress in the spine subsystem. Therefore simulation models were prepared to simulate the pre-stress in the neck by emulating the assembly process (see Figure 14). In a first step the spine subsystem was assembled without stressing the bumper elements of the vertebrae. This was followed by a second step where the spine was positioned into its design position, thereby stressing the bumper elements. Then, these results were used to create a model for finding the balanced state of equilibrium.

First step: assembly: The bumper is built in without deformation

Second step: The vertebra is rotated to initial position, so the bumper is pre- stressed

Figure 14: Setting up pre-stress in bumpers

Validation tests on system level

To validate the dynamic behavior three tests were used.

Denton calibration test - For this test, the torso of the dummy was mounted on a rack without pelvis and extremities (see Figure 15).

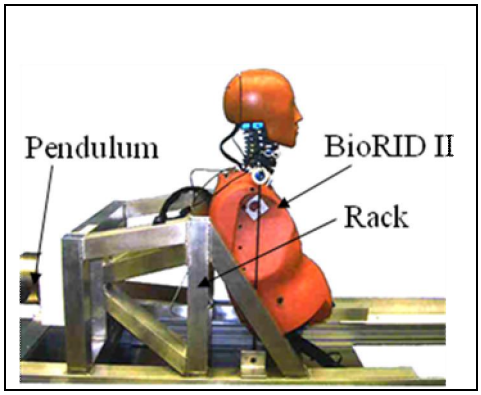

Figure 15: Experimental design of the Denton calibration test [1]

A pendulum accelerates the rack to get a defined longitudinal acceleration. The sled acceleration and velocity were preset in the simulation according to the calibration test [5].To pass this test it is necessary that several dummy responses stay within defined corridors, Figure 16 shows the location of these signals. In Figure 17 to Figure 21 the results of the FEM simulations are illustrated, all dummy responses pass the requirements. The requirements can be differentiated in a ñpeak corridorò requirement where signal peaks have to be within certain limits without respect to timing and a ñtube corridorò requirement where signals have to be within a corridor with respect to time.

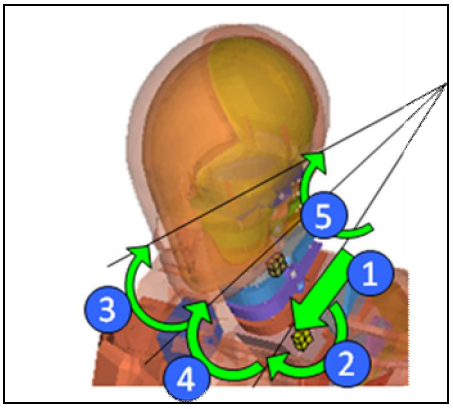

Figure 16: Location of the analyzed values
Here the measured values are shown (compare to Figure 17 - Figure 21)

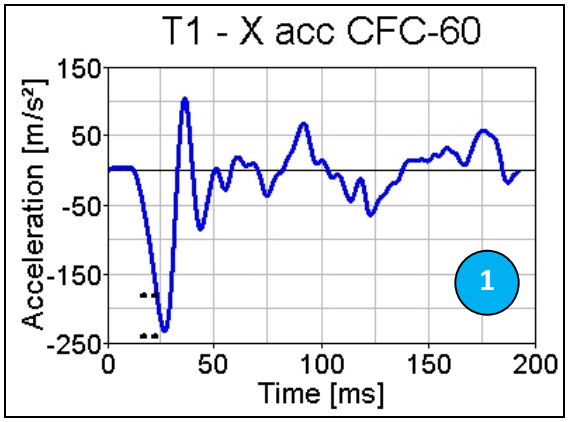

Figure 17: Acceleration of the 1st thoracic vertebra (Denton calibration test)
The initial peak of the T1 acceleration in longitudinal direction is within the peak corridor (dotted line).

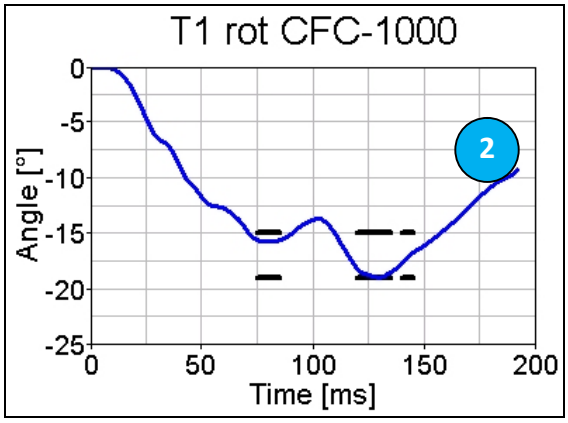

Figure 18: Rotation of the 1st thoracic vertebra (Denton calibration test)
The rotation of T1 stays within the tube corridor (dashed line) with respect to timing.

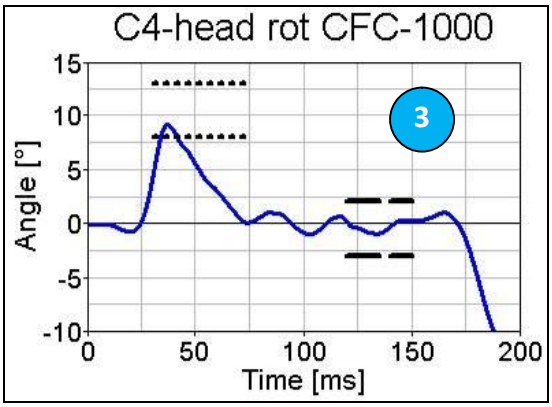

Figure 19: Relative rotation between head and 4th cervical vertebra
The initial peak of the relative rotation between head and C4 passes requirements of the peak corridor (dotted line) and the tube corridor (dashed line) in the later phase of the movement.

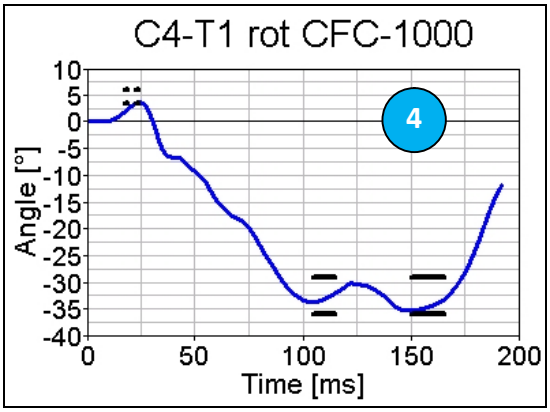

Figure 20: Relative rotation between 4th cervical and 1st thoracic vertebra (Denton calibration test)
The initial peak of the relative rotation between C4 and T1 passes requirements of the peak corridor (dotted line) and the tube corridor (dashed line).

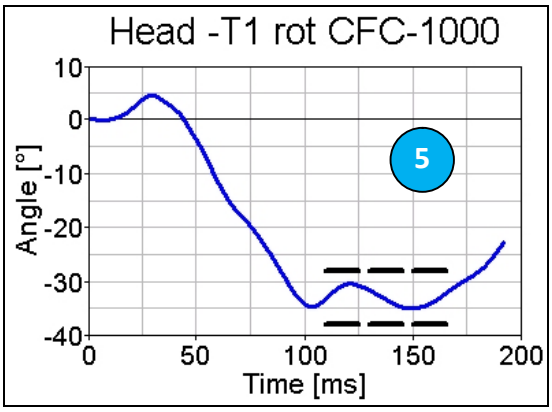

Figure 21: Relative rotation between head and 1st thoracic vertebra (Denton calibration test)
The relative rotation between head and T1 stays within the tube corridor (dashed line).

<u>Sled tests with torso only</u> - These tests were done to retrieve reliable validation data. For this reason a reproducible test-setup was chosen that was similar to the Denton calibration test, but includes an adjustable head restraint (see Figure 22). The rack was accelerated by a sled system (HyperG, [6]). The preset pulse is shown in Figure 23.

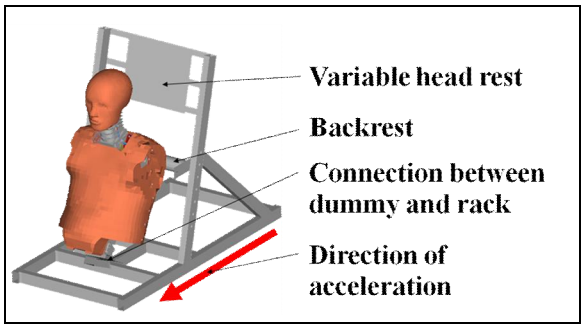

Figure 22: Configuration of the sled test

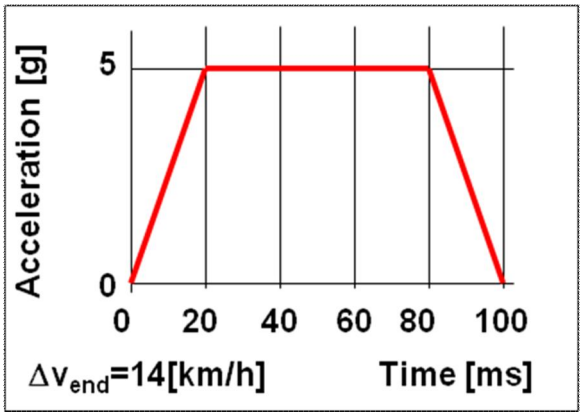

Figure 23: Acceleration of the sled test

For validation purposes, the results of the simulation are compared to the measurement data of the hardware test. Exemplarily, the accelerations in longitudinal direction of head, C4, T1 and T8 and the force in longitudinal and vertical direction between head and C1 are illustrated in Figure 24 to Figure 29.

All calculated dummy responses correlated to the experimental results in a satisfying manner. Experiments which showed the repeatability and reproducibility of the experiments were not performed within the scope of the project. Magnitude of peaks and the overall time history of the simulated dummy responses are expected to fit within the accuracy of repeated tests. For the accelerations of the different vertebrae some higher frequency oscillation is observed.

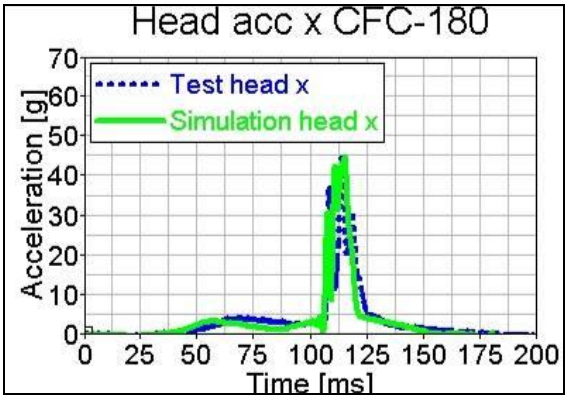

Figure 24: Acceleration of the head x (sled test)
Peak acceleration and time history of FEM simulation (solid line) and experiment (dashed line) of the head acceleration in longitudinal direction coincide sufficiently.

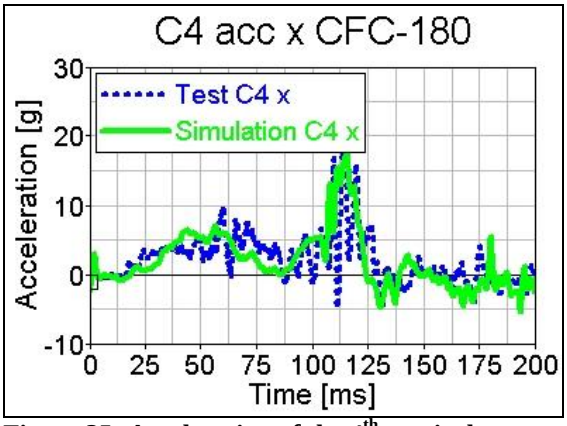

Figure 25: Acceleration of the 4th cervical vertebra x (sled test)
Peak acceleration and time history of FEM simulation (solid line) and experiment (dashed line) of the C4 acceleration in longitudinal direction coincide sufficiently. Higher frequency oscillation in the experiment is observed.

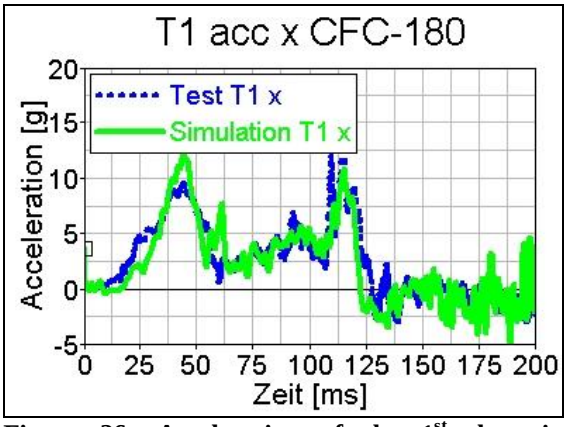

Figure 26: Acceleration of the 1st thoracic vertebra x (sled test)
Again, peak acceleration and time history of FEM simulation (solid line) and experiment (dashed line) of the T1 acceleration in longitudinal direction coincide sufficiently.

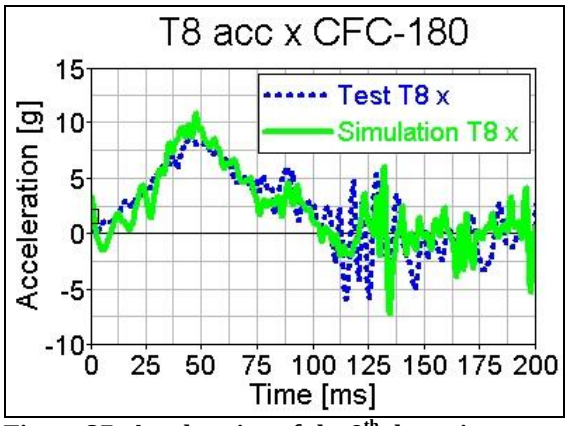

Figure 27: Acceleration of the 8th thoracic vertebra x (sled test)

A similar behavior as observed for C4 and T1 is also seen in T8 longitudinal acceleration.

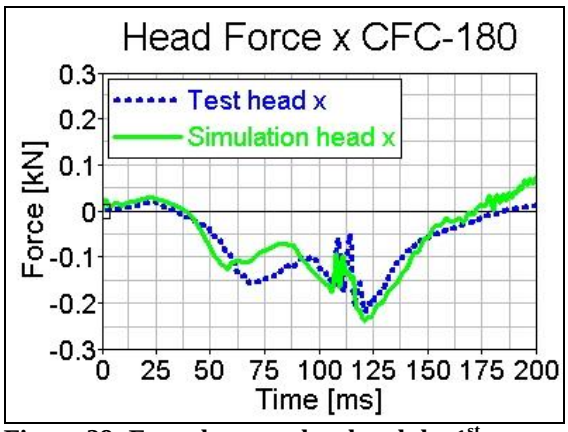

Figure 28: Force between head and the 1st cervical vertebra x (sled test)

Time history of the shear force between head and C1 show good accordance. The head restraint contact can bee seen between 100 and 125ms.

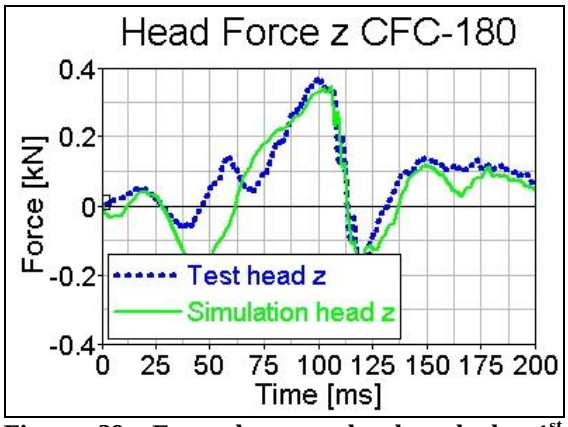

Figure 29: Force between head and the 1st cervical vertebra z (sled test)

Time history of the axial force between head and C1 show good accordance for the peak values. Minor deviation in the initial compression phase is observed.

The overall comparison between simulation and test showed that the model was able to reproduce the dynamic behavior of the hardware dummy in a satisfying manner.

CONCLUSIONS

Numerical FEM models of crash test dummies such as the BioRID II are a suitable tool for the development of vehicle safety systems. The BioRID II model allows for cost effective parameter studies for an improved head restraint and seat design. In order to predict the risk for Whiplash Assocociated Disorders (WAD) in a satisfying manner, high requirements on the prognosis quality of dummy responses are essential. In particular, modeling of the BioRID II is a difficult task because of the lack of geometry, material and other property data. Furthermore, the complex design of the articulated spine with pre-stressed elements requires a high level of detail in the model. In the present study a development process has been shown which is following the V model approach. The modeling of the dummy is based on the hardware which was disassembled and investigated. The full system of the dummy was broken down into subsystems and components. Modeling and simulation were performed on the corresponding level. The geometry of each component, the subsystem and full system was received by a combination of 3D scanner methods and manual measurements. Validation tests on different level of complexity were performed to retrieve reliable validation data.

Following this process of validation on different levels a FEM model with satisfying prognosis quality with respect to dummy kinematics, responses and injury criteria was built.

The limitation of this study is mainly related to further experimental test data. On the one hand repeatability and reproducibility tests to investigate the spread in the dummy responses would be helpful; on the other hand additional tests with other loading conditions would further improve the results.

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