Development of a Numerical Model of an Anthropomorphic Test Device for the Study of Human Related Impact Events

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ABSTRACT

The aim of this work is the development and validation of a numerical model of an Anthropomorphic Test Device for the simulation of impact events involving humans and consequently the study and development of crashworthy structures and restraint systems. The research approach consisted in a first validation by subcomponents of the numerical model, comparing the response of the model to the results of experimental tests specifically designed for this purpose. Then, the whole model response was observed and compared to experimental tests reproducing standard tests for the homologation of helicopter seats, in order to validate the model for use in a specific category of impact events. The simulation results showed very good agreement with the experimental tests, proving the Anthropomorphic Test Device numerical model a reliable tool for the analysis of analogous impact events. The model looks also promising for future developments, in particular it is suitable to be further improved in order to be able to reproduce a faithful response in different impact scenarios.

INTRODUCTION

Adequate biomechanical knowledge can help preventing most of the life-threatening and highly disabling injuries, through the study and design of crashworthy devices and safety restraint systems for ground vehicles and aircraft. A large amount of data in impact biomechanics is available nowadays, as the result of almost sixty years of laboratory research.

Anthropomorphic Test Devices (ATDs), commonly referred to as crash test dummies, are mechanical surrogates of humans. Crashworthiness engineers use ATDs to evaluate the occupant protection potential of various types of restraint systems in laboratory simulated collisions. Current ATDs reproduce faithfully human physical characteristics such as size, shape, inertial properties, stiffness and energy absorption and dissipation properties. The dummies' mechanical response can be easily evaluated by equipping the test devices with transducers that measure accelerations, deformations and loading of the various body parts. Analyses of these measurements are used to assess the effectiveness of crash safety systems. On the other hand, the significant increase in the use of computer simulations in the crash safety research has lead to the development of numerical models of vehicles as well as of the human body.

Mathematical models of the human body, in conjunction with the mathematical description of the vehicle structure and restraint systems appear to offer a very economical and versatile method for the analysis of the crash response of complex dynamic systems. This numerical approach can be applied in several areas of research and development, such as: reconstruction of actual accidents, computer aided design of crashworthy vehicles, seats, safety devices and roadside facilities, human impacts and biomechanics studies, occupant protection.

In this research, the Finite Element (FE) model of an aeronautical Hybrid III anthropomorphic dummy has been considered in order to evaluate biomechanics and loads determined by the impact of an aircraft in case of crash landing.

PHYSICAL ATD AND NUMERICAL MODEL

The Hybrid III 50th percentile male dummy is fully described in [1]. The National Highway Traffic Safety Administration (NHTSA) defines all the component assemblies of which the dummy consists of with detailed drawings. The single components of the dummy must be verified by prescribed testing procedures. Allowed materials are listed and characterized. Instrumentation on the dummy must comply with the standard specifications. An enhanced version of the standard Hybrid III 50th-percentile ATD was also designed to fulfill the needs of the aeronautical industry for the purpose of aviation seats certification [3]. Modifications are listed and defined in the Federal Airworthiness Regulation (FARs) [6].

A FE model of a standard Hybrid III 50th percentile male ATD was considered and adapted according to the aeronautical specifications. In fact, the original model refers to the dummy configuration used in the automotive industry to assess the crashworthiness performance of ground vehicles, which differ from the aeronautical version in the configuration of the lumbar spine element. In fact, impact phenomena in the aeronautical field are characterized by a dominant component of deceleration and velocity in the vertical direction and, therefore, a dominant spineward component on the occupant of the aircraft. On the other hand, in the automotive industry, the main component of acceleration in an impact event acts in the longitudinal direction. The different needs of the aeronautical industry has lead to the use of a specific crash test dummy with a straight lumbar spine element in order to include a load cell and measure the lumbar spine load. Therefore, the lumbar spine element in the model was modified and straightened, including a sensor for the measurement of the lumbar spine load. The two versions of the lumbar spine are shown in Figure 1.

The enhanced model consists of the same component assemblies defined for the physical ATD. It is composed by 109 parts, of which 61 parts were modelled as perfectly rigid and 48 as deformable. The model consists of 8525 nodes and 5688 elements, of which 1788 elements are shells, 26 beams, 3864 solids and 10 discrete elements. The correct degrees of freedom of the dummy, and consequently of human body, are reproduced by means of revolute and spherical joints, while the possible interaction between the parts is taken into account by defining the necessary contact surfaces.

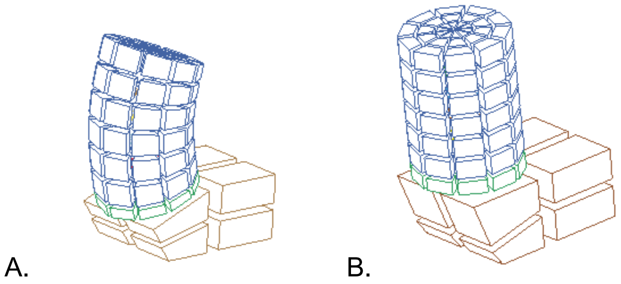

Figure 1: Standard (A) and modified (B) lumbar spine modelled element.

A numerical simulation offers the great advantage with respect to a physical test of being able to measure virtually every physical quantity at any instants in time. In fact, the numerical model of the dummy was endowed by numerical sensors in order to collect the same data as in a physical test, such as accelerations (head, thorax, pelvis, etc.), deformations and loads (lumbar spine) in various parts of the model. The dummy model is shown in Figure 2.

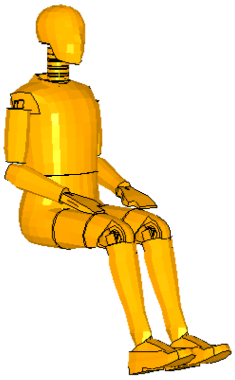

Figure 2: ATD finite element model.

SUBCOMPONENTS VALIDATION

Head. The head assembly consists of the following parts: skull, skin, accelerometers and head support disk. The standard specifications prescribe a calibration head drop test: the head shall be dropped from a height of 376 mm and the peak resultant acceleration shall be no less than 225 g and no more than 275 g. The acceleration-time curve for the test shall be unimodal to the extent that oscillation occurring after the main peak shall be less than ten percent of the peak resultant acceleration. Lateral acceleration shall not exceed 15 g.

A simulation was carried out dropping the head on a tough surface. The simulation results gave a peak acceleration within the prescribed range and an unimodal acceleration curve. The configuration of the simulated test and the head acceleration-time history normalized with respect to the maximum value measured are shown in Figure 3.

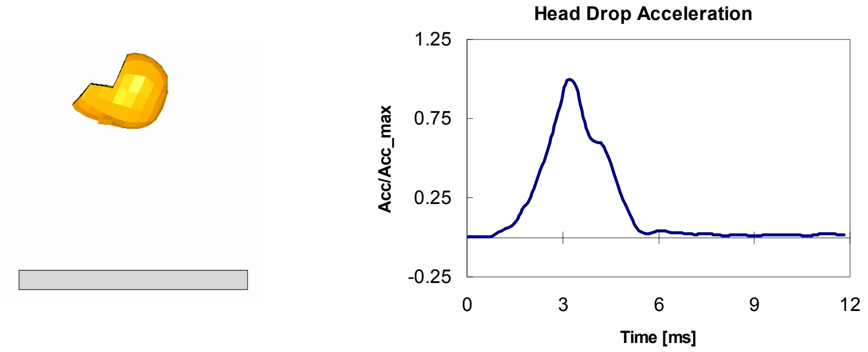

Figure 3: Head Drop Test simulation

Neck. Two calibration tests are prescribed for the neck assembly: neck flexion test and extension test. In both cases neck and head assembly are considered.

The head-neck assemblies are mounted on a rigid pendulum. The pendulum is then left free to impact a honeycomb block that imposes a prescribed deceleration pulse.

In the flexion test the condyle plane shall rotate between 64 and 78 degrees, which shall occur between 57 ms and 64 ms from time zero. The configuration of the simulated test as well as the flexion-time history (normalized with respect to the maximum calculated value) are provided in Figure 4. The neck flexion peak value is only slightly above the maximum allowable peak range and it occurs with a time delay, in particular, within 4% error on the peak value and within 13% error on the timing.

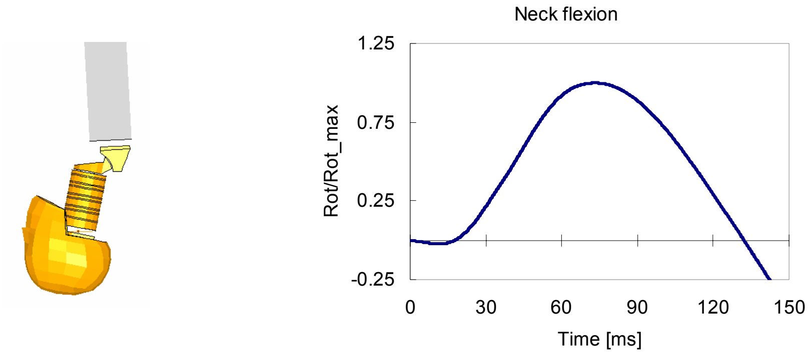

Figure 4: Neck Flexion Test simulation

The moment about the occipital condyles is required to have a maximum value between 88.1 Nm and 108.4 Nm, occurring between 47 ms and 58 ms. The maximum peak value is within 8% error, with a delay in time with an error of about 20%.

In the neck extension test, pendulum velocity at the moment of impact shall fall between 5.94 m/s and 6.19 m/s. The maximum rotation of the occipital condyles plane shall be comprised between 81 deg and 106 deg., which shall occur between 72 ms and 82 ms from time zero. The moment about the occipital condyles is calculated as in the neck flexion test and it shall have a maximum between 52.9 Nm and 80 Nm, occurring between 65 ms and 79 ms. The maximum rotation of the neck about the occipital condyles in the extension test results within the prescribed range, although occurring with a certain delay in time. The maximum peak of the condyles moment is less than 15% above the range and it occurs consistently with a delay in time as in the neck rotation history.

Thorax. A pendulum impact test is prescribed to measure the response of the thorax. The impactor velocity measured by a test probe shall be 6.71 m/s +/- 0.12 m/s. The thorax shall resist with a force between 5160 N and 5894 N, with a maximum sternum deflection in an interval between 63.5 mm and 72.6 mm. The internal hysteresis in each impact shall be more than 69% but not less than 85%.

The configuration of the simulated test and the computed sternum deflection-time history (normalized with respect to the maximum calculated value) are shown in Figure 5.

The maximum computed sternum deflection falls within the prescribed range, corresponding to a maximum resistive force with a relative error less than 10%. Hysteresis ratio results clearly within the prescribed range.

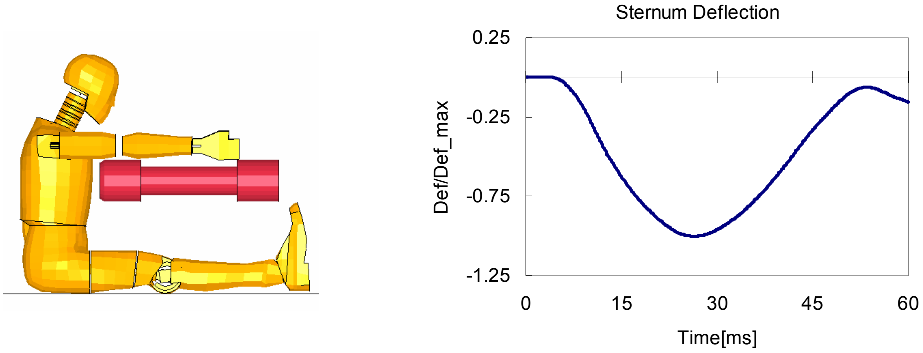

Figure 5: Thorax Impact Test simulation

Knee. The knee impact test measures the response of the knee assembly when impacted by a 5-kg impactor with a velocity of 2.1 m/s. The peak knee impact force, which is the product of the impactor mass and deceleration, shall have a minimum value of no less than 4715 N and a maximum value of no more than 5782 N.

The simulated test and the history of the impact force (normalized with respect to the maximum calculated value) are shown in Figure 6. Impact force falls within the prescribed range.

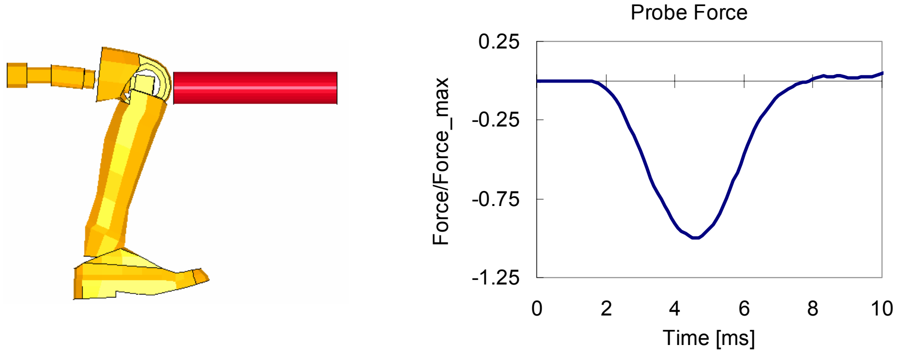

Figure 6: Knee Impact Test simulation

SIMULATION OF THE STANDARD "DOWN TEST"

The Federal Aviation Administration (FAA) prescribes two standard tests for the homologation of an helicopter seat: the "Forward Test" with a dominant longitudinal deceleration pulse which proves to be critical for the structure of the seat itself and a "Down Test" that simulates the conditions of a crash landing with a dominant vertical deceleration pulse. This last condition proves to be extremely critical for the occupant, since it presents a high spineward deceleration component, determining consequently high levels of lumbar spine loads.

Experimental test [3]. The conditions of the *"Down Test"* were considered for the validation of the ATD finite element model which is the objective of this work. The configuration of the test requires that the helicopter and hence the seat in test has a 60-degrees pitch angle with respect to the forward direction, with the pitch axis lying in a vertical plane defined by the velocity vector and the longitudinal axis of the helicopter. The prescribed theoretical deceleration pulse is triangular, reaching the maximum value of 30 g in 31 ms and decreasing to zero in 31 ms, as well.

Comparison tests for the validation of the numerical model of the Hybrid III dummy were provided by the Netherlands Organization for Applied Scientific Research (TNO) within the test campaign for the Helisafe program [3]. In particular, the reference tests were accurately carried out with the objective to assess the performance of the FAA Hybrid III dummy, by isolating as much as possible the response of the dummy from the one of the seat.

The dummy was placed on a rigid seat, constituted by two thick steel plates and a thin layer of Teflon was interposed between the dummy and the seat The configuration of the test is shown in the left column in Figure 9.

The seat was positioned on a test sled that during the test is accelerated by an oleo-pneumatic system, giving the correct triangular acceleration pulse. The dummy was then constrained to the seat by means of a four-point harness and instrumented according to the standard specifications.

FE model. In the FE simulations the configuration of the experimental tests was faithfully reproduced. The steel seat was modelled with shell elements and constrained to a perfectly rigid structure, representing the test sled. The dummy FE model was positioned with an iterative procedure to obtain the correct position of the model on the seat as in the real tests. In fact, several test simulations demonstrated the strong sensitivity of the response of the dummy to its position on the seat. No Teflon plate was included in the model, but its effects were reproduced by calibrating the friction coefficients in the contact between the dummy limbs and the seat.

A four-point harness was explicitly modelled around the dummy FE model, using 2D shell elements in the region of contact between the dummy and the belts and 1D elements for the other segments. The belt was given characteristics measured in a tensile test performed at TNO. A retractor system was also included in the model. The complete model including all its parts (dummy, seat, seatbelts) is shown in the right column in Figure 9. The deceleration pulse from the experimental test was given to the sled in the model as a prescribed motion boundary condition. Gravitational loads were applied to the model, reproducing the exact conditions of the test, providing a settling time in order to achieve an equilibrium configuration of the dummy model subjected to these body forces.

Model calibration. The main features of the model that needed to be assessed and calibrated were contact definitions and frictional coefficients.

Two categories of contacts can be identified: contacts among parts of the dummy model and contacts between the dummy and the seat. In order to simulate the correct motion of the dummy, it is fundamental to model the contact surface of the parts of the dummy with themselves, in particular the following contact surfaces were defined: chin with thorax, hands with thighs and knees, upper body with abdomen and limbs, segments of the legs with themselves. Besides, it was important to model the contact of the femurs with the shell of the pelvis. In fact, it was noticed that the lack of this contact changed significantly the load transfer mechanisms to the lumbar spine. Regarding the interaction between the dummy and the seat, three main contact definitions were considered: a surface-to-surface contact type between the dummy's back and limbs with the backseat, a surface-to-surface contact type between limbs and thighs with the seat and a nodes-to-surface contact type between the feet and the sled structure. The two distinct contact definitions involving the backseat and the seat were necessary to set different frictional coefficients to simulate the presence of a layer of Teflon covering only the seat.

A sensitivity analysis was carried out in order to determine the effects of the frictional coefficients between steel and PVC and between Teflon and PVC. It was noticed that the static friction coefficient played a more important role than

the dynamic coefficient, since the relative velocities between the parts in contact were low.
A static friction coefficient of 0.40 was used between steel and PVC. On the other hand, the more realistic results in terms of sliding of the dummy on the seat and consequently of the significant parameters of the simulation were obtained with a static friction coefficient of 0.17 for the contact Teflon-PVC.

Simulation Results. The model was used to simulate the conditions of the vertical test prescribed by the specifications. The experimental deceleration curve was imposed as acceleration boundary condition. Then, data from the simulation were collected and compared to the corresponding experimental data. Particular attention was given to the lumbar spine load and the head acceleration.
The force-time history of the lumbar load (normalized with respect to the experimental peak load) is shown in Figure 7. The numerical-experimental correlation is satisfactory: the simulation results show a slightly faster growing lumbar load than the experimental test; despite of this, the agreement in terms of maximum peak load and duration of the load pulse is very good. The maximum lumbar load registered during the numerical simulation showed only a 5% error with respect to the experimentally measured peak load.
The comparison between the head acceleration-time histories of the numerical simulation and of the TNO test is provided in Figure 8. It can be noticed that the two histories look similar, although the numerical results are affected by high-frequency noise. This fact is fairly common in explicit dynamics finite element codes and related to the adopted integration scheme.
Qualitatively, the simulation and the test are compared in Figure 9. The overall behaviour of the dummy is consistent in the two sequences of events, as well as the timing of the phenomena corresponds almost perfectly.

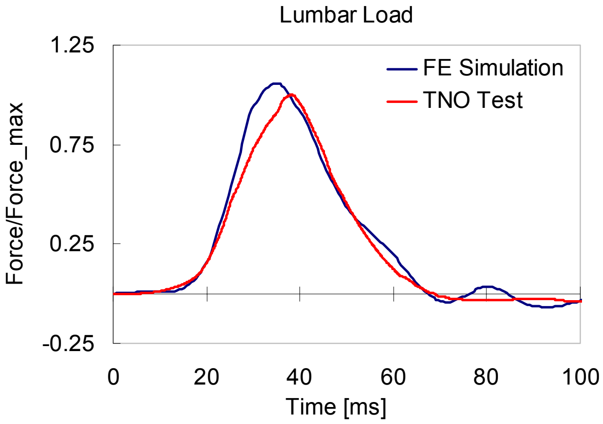

Figure 7: Simulation results for Down Test, lumbar load.

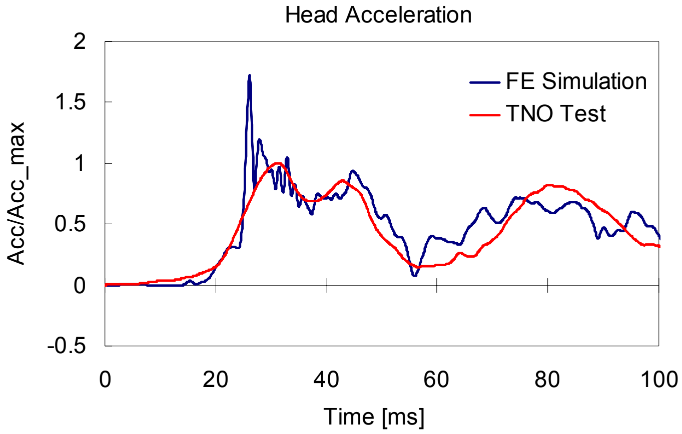

Figure 8: Simulation results for Down Test, head acceleration.

CONCLUSIONS

The calibration of a numerical model of an ATD to be used for the assessment of the crash performance of aeronautical seats has been performed in this study. A first phase was focused on the assessment of the main subcomponents of the dummy, comparing the simulation results with the FARs requirements. Subsequently, the model was tested in a typical impact condition of an aeronautical seat. Material models and parameters, as well as contact interfaces within the model were calibrated.

Simulation results showed good agreement with the reproduced physical tests, thus proving the model a reliable tool in the study of similar impact conditions. Further improvements are achievable. In particular, the research continues and it is aimed at extending the validity of the model for the analysis of different impact conditions.

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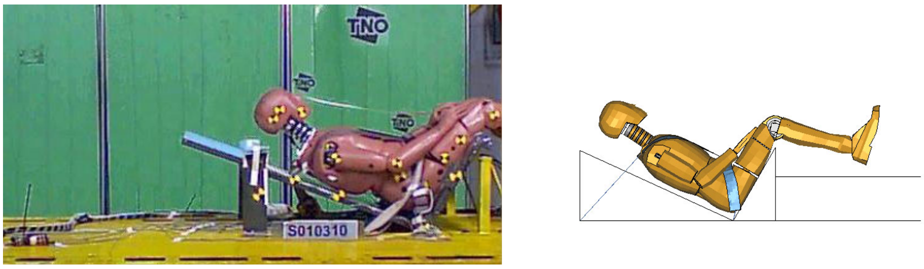
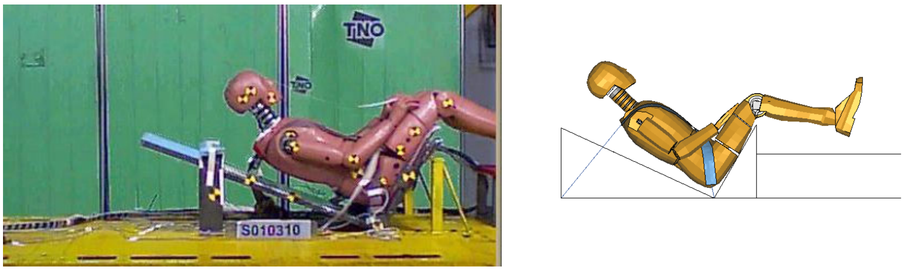
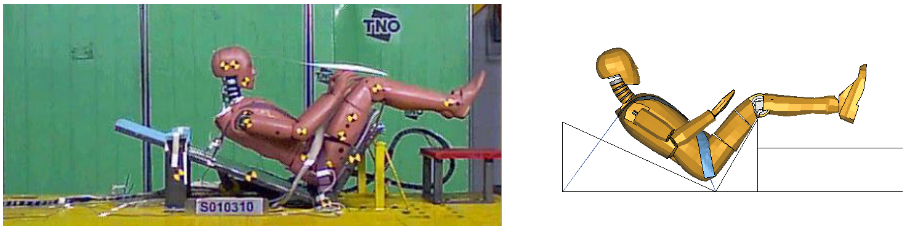
t = 0 ms



t = 50 ms



t = 70 ms



t = 100 ms

Figure 9: Experimental test (LHS) and numerical simulation (RHS) sequence of events.