DEVELOPMENT OF A HYBRID III LOWER LEG COMPUTER MODEL

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ABSTRACT

With the introduction of the lower leg injury criteria in the new European Frontal Impact Legislation, the leg kinematics and loading mechanisms must be considered at an early stage in vehicle development programmes. Finite Element codes such as LS-DYNA3D are used increasingly to model occupant/structure interactions for vehicle design, from concept to the final restraint system optimisation. A fully validated Hybrid III lower leg model is consequently an essential tool in the vehicle design process. However, due to the complex nature of the materials and geometry of the lower leg and footwell, development of such a model presents a number of problems.

In the collaborative LLIMP project (Lower Leg Injuries and Methods of Prevention vehicle design project), MIRA, with the project sponsors, Jaguar, Ford and Rover, has developed a Finite Element computer model of the Hybrid III lower leg which can be attached to a full Hybrid III Finite Element dummy model. The model has been used to support vehicle design as well as evaluating the effects of footwell intrusion and occupant position on lower leg injury criteria. The paper presents the development of the lower leg model, which includes the use of lower leg component tests and HyGe sled tests to validate the material models, contact characteristics and load levels. HyGe sled tests have been simulated to which lower leg kinematics, loading mechanisms and injury criteria have been correlated.

INTRODUCTION

In recent years there has been a significant reduction in the number of fatalities and life threatening injuries sustained by occupants in car accidents. This can be accounted for by the development and inclusion of safety features, such as air bags and seatbelt pre-tensioners, as well as improvements in the crashworthiness of vehicle structures.

However, with increased accident survivability there has been an increase in the effect on the lower legs. While lower leg injuries are not life threatening, serious fractures in the foot and ankle can cause permanent disability.

The development of a Finite Element model of the Hybrid III leg has been necessitated by the increased interest in reducing injury of the lower extremities. A numerical model would provide an essential tool to assist in the understanding of the complex leg kinematics and loading mechanisms experienced by the occupant in the crash event.

It is intended that the model is used as a development tool, for evaluation of lower leg kinematics and loading mechanisms under different footwell intrusion profiles and occupant positions. The model would also provide useful information in the early stages of vehicle development to mitigate injury and enable causes of injury to be designed out.

In the initial stages of the LLIMP project, analysis of crash test results highlighted the importance of evaluating the lower leg kinematics in order to understand the complex loading mechanisms, [1]. Therefore the computer model was required to accurately represent the kinematics, contributing to an accurate representation of the loading mechanisms in the leg.

OVERVIEW OF OCCUPANT SIMULATION TOOLS

Currently engineers have a number of simulation tools available to them, and with hardware developments, these tools are becoming ever more sophisticated. In codes such as LS-DYNA3D it is possible to run in excess of one million degrees of freedom structural models including occupant, restraint system and the vehicle structure.

In the past, when considering the lower legs, analysis has been limited by the information that could be extracted from the models. Rigid body occupant models, (Figure 1), represent general kinematics effectively but are often unable to extract injury data and simulate complex loading mechanisms. Contact representation is often inaccurate due to poor dummy surface representation with ellipsoid models and local stiffness imprecisions in the vehicle structure, occupant or occupant's clothing and shoes.

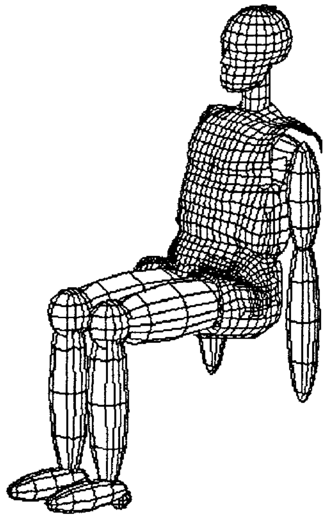

Figure 1: Rigid occupant model.

Finite Element Analysis with codes such as LS-DYNA3D has a major advantage over other simulation tools in the way it is possible to model the occupant and it's environment in detail to represent the complex interaction between the structure and occupant, [2,3].

MODEL DEVELOPMENT

Methodology

The lower leg model needed to be closely representative of the Hybrid III test device to accurately simulate the complex 3D motion, and assist in validation of the proposed five phases of quasi static and dynamic loading experienced by the leg over the duration of an impact, [1].

The model of the leg needed to be geometrically accurate to provide a detailed surface representation ensuring timing and mechanisms of contact are indicative of those seen in test. Inertial properties of individual components are also realistically represented due to the accurate geometry, and material densities used in the leg model.

Material characteristics in the Hybrid III leg Finite Element model account for nonlinearities of the foam materials, and hysteretic behaviour where relevant.

Each load cell in the leg is individually represented with a translational or rotational spring to provide a means for output of forces and bending moments experienced by the leg.

Extra accelerometer output is provided by accelerometers on the leg model adjacent to the knee and ankle and in the heel and toe. These are used to assist in the understanding of leg kinematics, [1].

To create a robust leg model that can be used with confidence, a development methodology was devised to incorporate a variety of tests, designed to provide supporting data for the model creation. There were two main test categories used in the development of the Finite Element leg model:

- Component tests; these were used to develop material models and validate load cell models.
- HyGe sled tests; these were used to validate the model as a complete system, including legs and rigid torso representation.

Model Construction

To accurately simulate lower leg kinematics and complex loading mechanisms, it was essential that the inertia and mass distribution through the model was representative of the Hybrid III test device. To this end, the foam covering and steel skeleton of the Femur, Tibia and Foot were modelled to be geometrically accurate using solid hexahedral and wedge elements, (Figures 2 and 3). Table 1 summarises the mass contribution from components in the legs and compares with Hybrid III mass information, [4].

'Flesh' foam surrounding the Tibia and Femur are represented with foam material models in LS-DYNA3D. Soft foam materials are susceptible to hourglass and contact problems due to the large strains involved. Therefore care was taken in the selection and correlation of materials to create a robust model, able to withstand high energy impacts without causing solution instabilities.

Instrumentation in the dummy leg was represented in the model to enable a direct comparison to be made between test and Finite Element analysis results. Accelerometers in the leg and foot are represented to give acceleration output in local co-ordinate systems. F_x and F_z load cell outputs are obtained from the model using translational springs. M_x and M_y are extracted from rotational springs at the load cell locations. Each of the springs used to output load cell data has an equivalent translational or rotational dashpot damper, damping out high frequency interference through the leg.

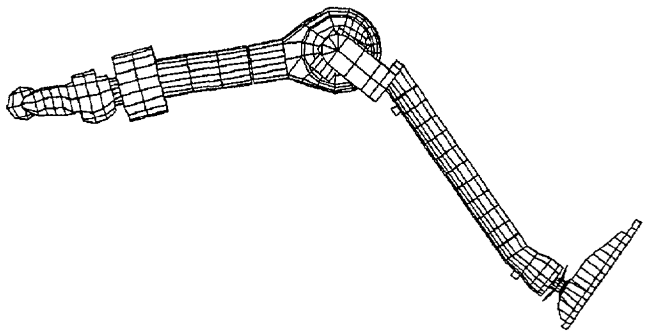

Figure 2: Skeletal leg model.

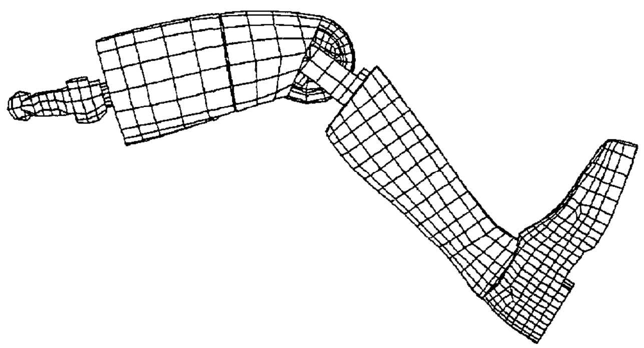

Figure 3: Complete leg model.

The complex interaction between the foot and shoe provide a significant obstacle to overcome. A limited understanding of the behaviour of contact between the foot and shoe was gained via component tests. Details of the component tests follow.

Table 1: Mass Properties of the Hybrid III Leg.

	Hybrid III (kg)	DYNA3D model (kg)
Foot	1.25	1.3
Lower Leg	3.28	3.3
Upper Leg	6.22	6.2

To date, the joints in occupant models have generally been represented using spherical joints, and their stiffness and rotation limits governed by nonlinear rotational springs. The magnitude of joint stiffness is highly variable from test to test, and throughout the duration of a test is dependent on the mechanism of loading through the joint. This is especially important when we consider the ankle joint in the lock up state. Throughout the lock up state the mechanism of locking can change between longitudinal and lateral lock up, depending on external factors, such as footrest and pedal design. The loading mechanism on the ankle joint also causes large variability in the ankle's rotational stiffness. This provides a significant obstacle when creating the DYNA3D model. Because of the high energy and short duration associated with impacts it is valid at this stage in the model development to assume that the ankle joint stiffness will have negligible effect on the loads measured in the legs. Although the ankle in the model has no rotational stiffness, the lock up state of the ankle is enabled by the accurate representation of the foot skeleton and lower Tibia, (Figures 4 and 5). The curvature of the ankle stop is represented both laterally and longitudinally to allow the nominal 45° stop angles in dorsiflection, and 30° stop angle in inversion and eversion.

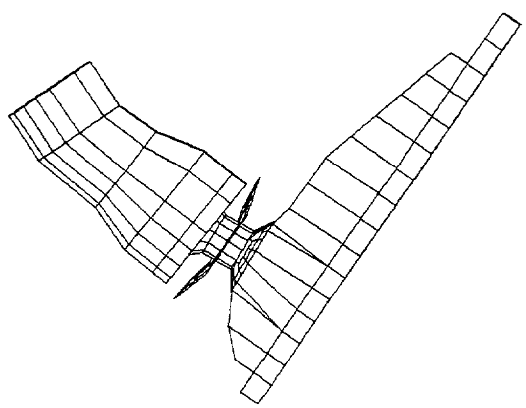

Figure 4: Accurate ankle joint representation.

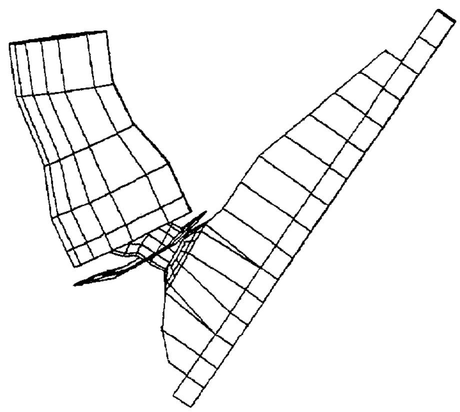

Figure 5: Ankle joint in lock up state.

Accurate geometrical representation was also considered important in the knee where there is both rotational and translational components of the joint dynamics. The rotation was governed in the model with a geometric joint definition, only allowing rotation about a single axis. The knee slider is controlled using a nonlinear translational spring.

Model Correlation

To correlate a Finite Element model with the complexity of the Hybrid III leg it is necessary to break the model into smaller sub-systems and correlate these models to physical component tests. Using this approach minimises the complexity of the problem and provides a method to highlight areas of the computer model that require attention. Once the sub-systems are understood they are assembled to form the complete structure. Finally the complete system is correlated to test. This modelling philosophy was considered to be essential to the development of a robust model of the Hybrid III leg.

The lower leg physical component testing consisted of three types of drop test. Each of the tests was repeated several times, and at different speeds to allow for experimental inaccuracies and rate dependency in the leg and foot foam. After each test, components were given time to recover before being re-tested. This was considered to be especially important when testing viscous foam materials.

Foot Drop Tests

Drop tests were used to develop the foam material model for the Hybrid III foot, (Figure 6). Twelve drop tests were carried out, including tests on both the left and right foot. Three velocities were used to enable the assessment of rate effects in the foam. The ankle was fixed rigidly for each test to minimise boundary effects. An aluminium headform impactor of mass 6.8kg was dropped onto the heel. An accelerometer was fixed to the impactor to measure acceleration in the direction of impact. This output was integrated to give the velocity and displacement of the impactor.

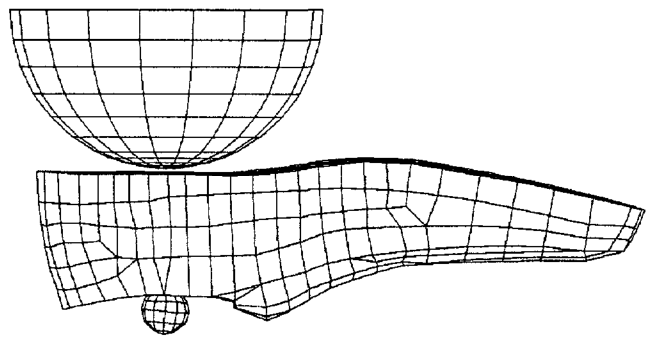

Figure 6: Foot drop tests performed at 1.5m/s, 2.5m/s and 3.5m/s.

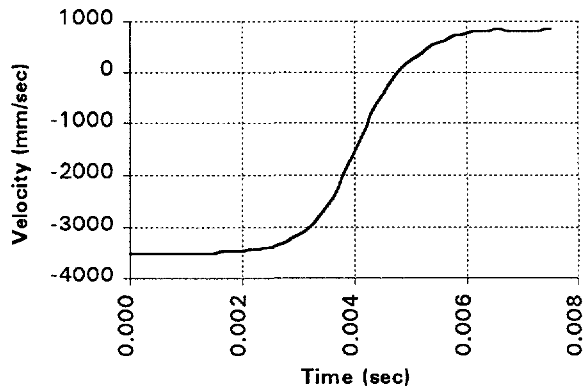

Figure 7: Impactor velocity highlighting energy absorption properties in the foot foam.

A significant feature of the foam in the foot is highlighted by the velocity trace, (Figure 7). The impact velocity is approximately 4.5 times the magnitude of the rebound velocity, suggesting that energy is absorbed by the foam. Therefore the choice of foam model needed to account for significant energy absorption. The large amount of hysterisis in the foam was overcome by using the Fu Chang foam model and including a high value of Young's relaxation modulus, [5]. LS-DYNA3D's implementation of the Fu Chang foam model can account for rate dependency in the material. Rate effects are included by supplying a number of stress strain relationships at given strain rates. This feature of the material model was not used in the development of the foot foam model, as the strain rate was not considered important over the range of impact velocities that the foot experiences. The implemented stress strain characteristic was considered valid for the strain rates encountered in this work.

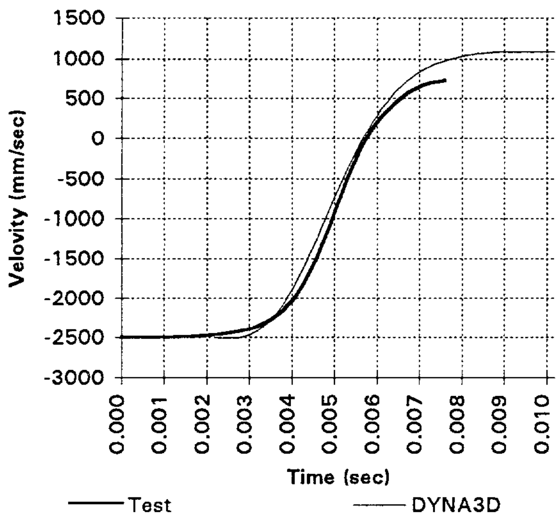

Figure 8: Impactor velocity comparing computer simulation to physical test.

The impactor accelerations and velocities from the Finite Element model correlated well to results from the physical test, (Figure 8). The energy absorption characteristic of the foot was considered to be the most important feature to represent. Without this, problems would be introduced with elastic impacts causing unrepresentative lower leg kinematics when the leg model was assembled as a complete system.

Shoe Drop Tests

To investigate the behaviour of the shoe the boundary conditions were identical to those used in the drop tests used for the foot investigation, (Figure 9).

Comparing acceleration traces of drop tests performed with and without the shoe displays an unexpected result, (Figure 10). Knowing that the sole of the shoe is stiffer than the foam of the foot, it was expected that the impactor should decelerate at a faster rate when dropped onto the foot with shoe. This was not the behaviour exhibited in test, suggesting that the interaction between the shoe and foot is an important feature of the overall foot/shoe system adding additional complexity to the creation of a computer model.

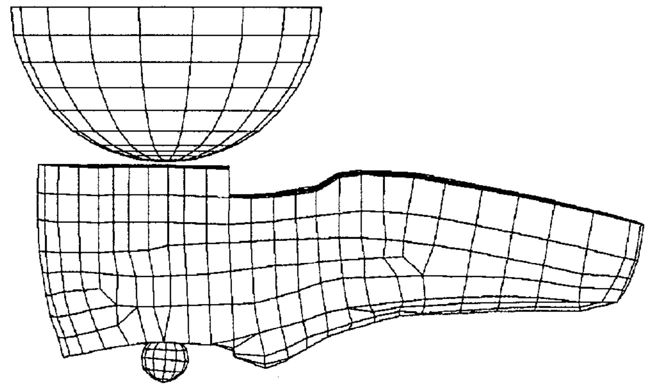

Figure 9: Shoe drop tests performed at 1.5m/s, 2.5m/s and 3.5m/s.

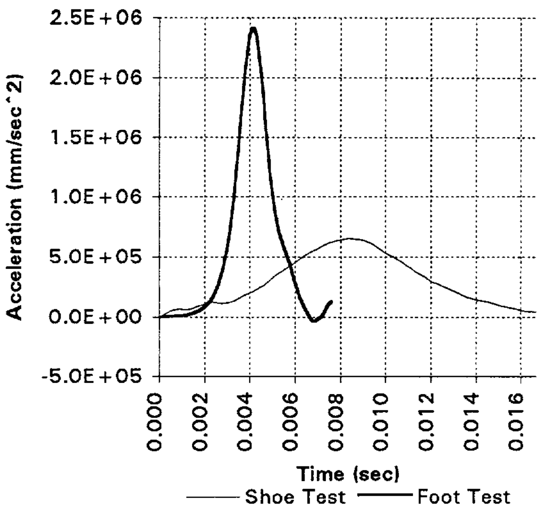

Figure 10: Comparison of impactor acceleration traces between drop tests performed with and without the shoe.

Lower Leg Impact Tests

Validation of the behaviour and output of the load cells in the lower leg was approached using a series of 24 drop tests. Three boundary condition combinations were tested at varying impact speed to provide data for correlating the bending moments and forces in the model to those measured in test. Each test was repeated twice to allow for experimental variability.

The 3.6kg impactor was designed specifically for these leg tests. It's impact face was rectangular with smoothed edges to reduce the risk of damaging the leg. The impact locations are shown in Figure 11. The knee joint was pinned to allow rotation only about the local y axis. Constraints were applied to the ankle to allow rotation about the y axis and translation in the z axis.

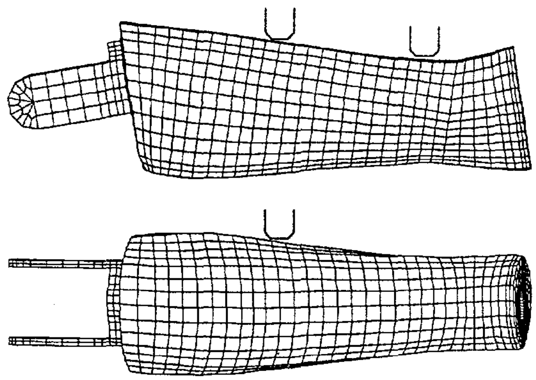

Figure 11: Lower leg impact tests - impact locations for Tibia front and side tests.

Upper and lower tibia M_y, M_x, F_y and F_x were investigated using data from impacts to the front face of the Tibia.

Output from the load cells in the Finite Element model was seen to be significantly linked to the characteristics of the foam surrounding the skeleton of the lower leg. Therefore correlation of the load cells was achieved by considering the properties of the foam. Impacts with the Tibia were seen to absorb less energy than those with the foot, so a less 'expensive' urethane material model was chosen to model the foam, requiring less CPU time to solve.

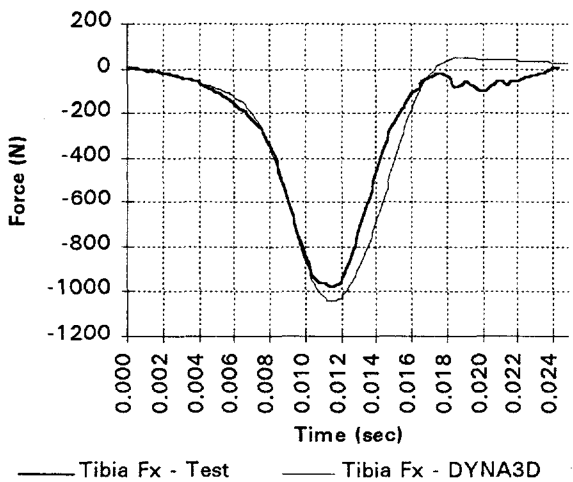

Figure 12: F_x in test and model for lower leg component tests.

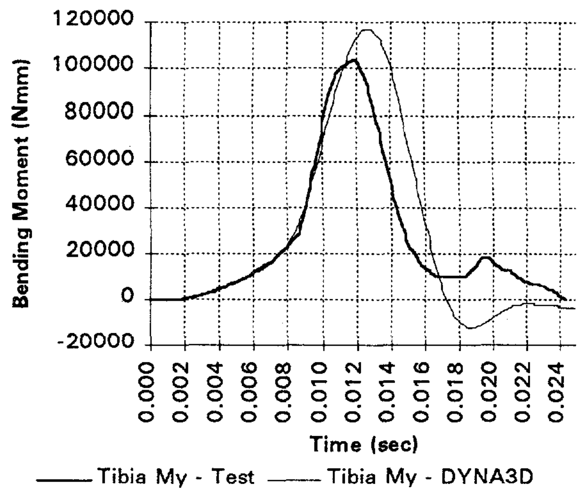

Figure 13: My in test and model for lower leg component tests.

HyGe Sled Tests

To correlate the complete occupant system, with the finite element legs attached to a rigid upper body, a series of four HyGe tests were devised. The tests were designed to have boundary conditions that would translate into a DYNA3D model with minimum complication, reducing sources of error and the number of unknown variables.

The test matrix incorporated two frontal impact pulses; one representative of a medium car, the other representative of a larger vehicle. The only other significant differences between tests were in the footwell, which consisted of two rigid planes with adjustable gradient, so each plane could be positioned at either 30° or 60° to the horizontal. Restraints were kept to a minimum, with only a length of low strain webbing to represent the belt system. No seatbelt retractor was included but the webbing had ample slack to allow enough forward excursion of the pelvis to permit the Tibia to reach a vertical position. Feet were positioned so that initially they were not in intimate contact with the footwell.

To gain confidence in the performance of the Finite Element leg model, the modelling of HyGe tests was split into two distinct phases. The first phase considered a rigid ellipsoid occupant. The second phase used the modified model with Finite Element representations of the legs. In both phases the HyGe sled was represented in the model by rigid planes fixed in space, (Figure 14).

Using the rigid occupant enabled the general occupant kinematics to be considered, and the occupant environment variables to be tuned without additional complication due to inclusion of the new legs. Once a good correlation of head, chest and pelvis acceleration had been achieved, the exercise could be repeated, but with emphasis on the performance of lower leg kinematics and loading in the model.

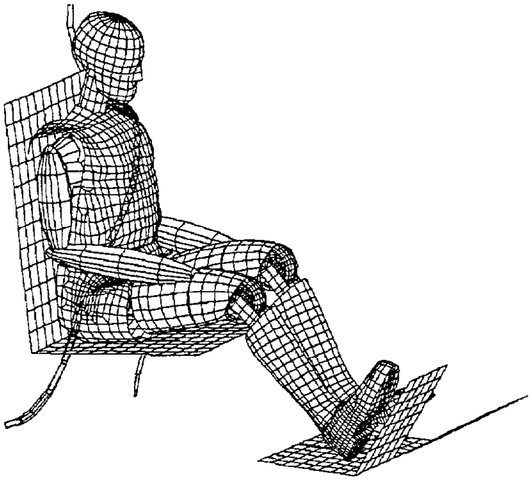

Figure 14: HyGe test used in correlation phase.

The correlation results for the chest and pelvis accelerations for the rigid ellipsoid model are shown in Figures 15 and 16. These results continue to be valid, with only minor differences when the ellipsoid legs are replaced with the FE representations. The global kinematics of upper body parts of the ellipsoid model are good, but closer inspection reveals that the dynamics of the feet and lower legs are unsatisfactory. This is due to the unrepresentative ellipsoid surface definition and lack of simulation of local stiffness variation in the occupant model.

Both the global and lower leg kinematics in the second phase modelling of the HyGe tests were very good. This lead to accurate output from load cell models that correlated well to test data. M_y and F_z all show the main peaks and troughs throughout loading. A sample of the correlation plots between test and analysis results for load data in the leg is shown in Figures 17 and 18. A sequence showing how the leg model behaves in the HyGe test is shown in Figure 19.

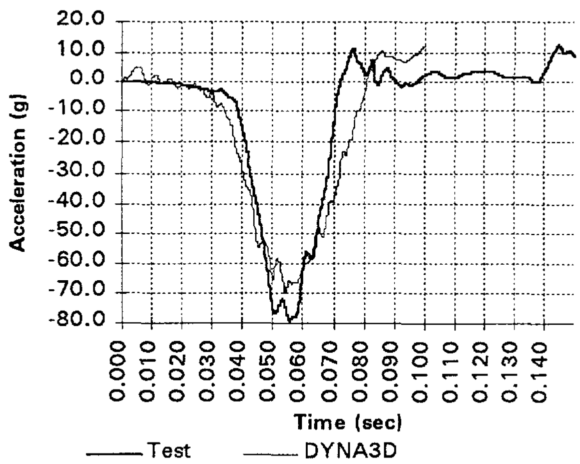

Figure 15: Chest acceleration of occupant in HyGe test.

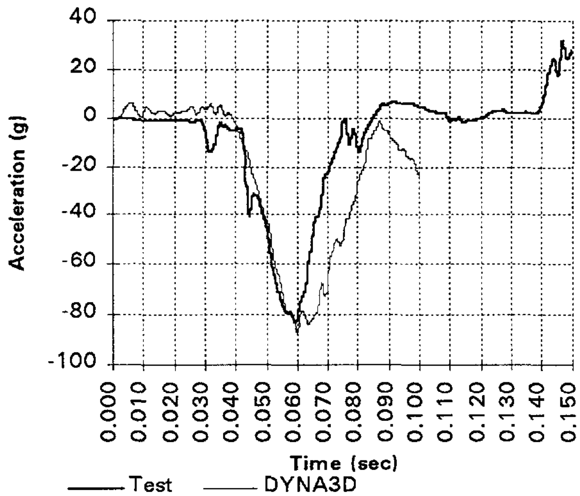

Figure 16: Pelvis acceleration of occupant in HyGe test.

Achieving good correlation between the model and HyGe tests, has given confidence in the numerical model. It can represent two dimensional behaviour, but boundary conditions in the tests did not allow for effects such as feet sliding off pedals or interaction between the legs and knee bolsters or facia. These effects add a further dimension to the behaviour of the legs, with the ankle joint moving into inversion or eversion. The loading mechanisms caused by these three dimensional effects are not yet fully understood, so it is not yet possible to validate these effects in the model. It is hoped however, that the model will assist in the understanding of three dimensional behaviour, in order to enable correlation to full scale crash tests.

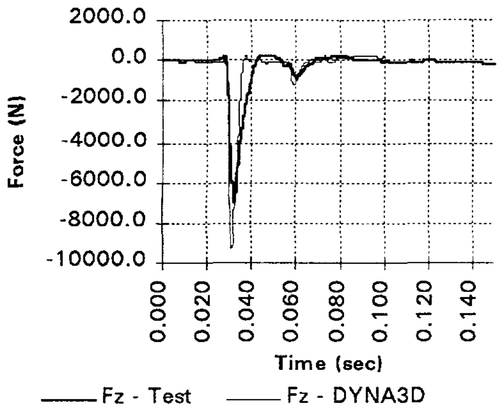

Figure 17: Right lower Tibia F_z force in HyGe test.

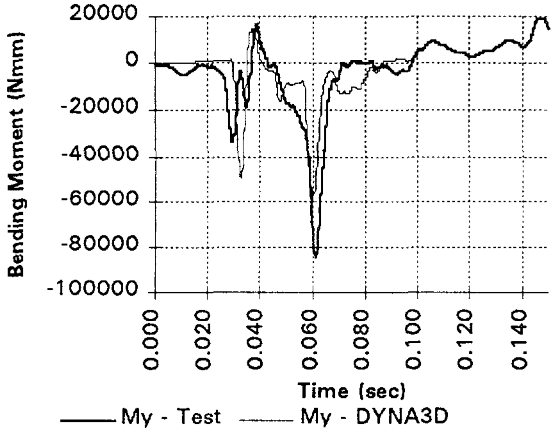

Figure 18: Right lower Tibia M_y bending moment in HyGe test.

CONCLUSIONS

The model is a useful tool that can be used to consider the two dimensional leg behaviour. The development of the Hybrid III lower leg has highlighted the need for a better understanding of three dimensional occupant lower leg behaviour.

Through the intensive correlation exercises performed on the leg components and complete occupant model we can be confident that the model provides accurate loading and kinematic data to assist in the early stages of vehicle design and development to mitigate injury.

The Finite Element model has helped considerably in the advancement in understanding of the two dimensional behaviour of the Hybrid III lower leg. The phases of loading and kinematics that the leg experiences during impact can be represented realistically with a good degree of correlation to test results. This has enabled the investigation of parameters in the footwell region that effect injury in the lower leg, [6]. There are still considerable obstacles in accurately representing the three dimensional behaviour of the legs, with effects such as feet sliding off pedals and nonlinear intrusion profiles being difficult to simulate.

FURTHER WORK

MIRA through the MISTIQUE project, (MIRA Intrusion Simulation Technique), have developed a test rig to be used in conjunction with the HyGe reverse accelerator. The MISTIQUE rig simulates footwell intrusion using rotating and translating planes. On completion, it is hoped that the lower leg computer model and MISTIQUE rig will work in partnership to aid the understanding and development of footwell design to mitigate lower leg injury. In the first instance the test rig will supply more data to further increase confidence in the Finite Element model and bridge the gap between HyGe test and complete vehicle frontal crash tests.

The leg model is currently being used in vehicle design to look at effects on the occupant due to intrusion. The model will be used from early stages in vehicle development programmes to reduce occupant injury, and increase awareness of the factors contributing to leg injury.

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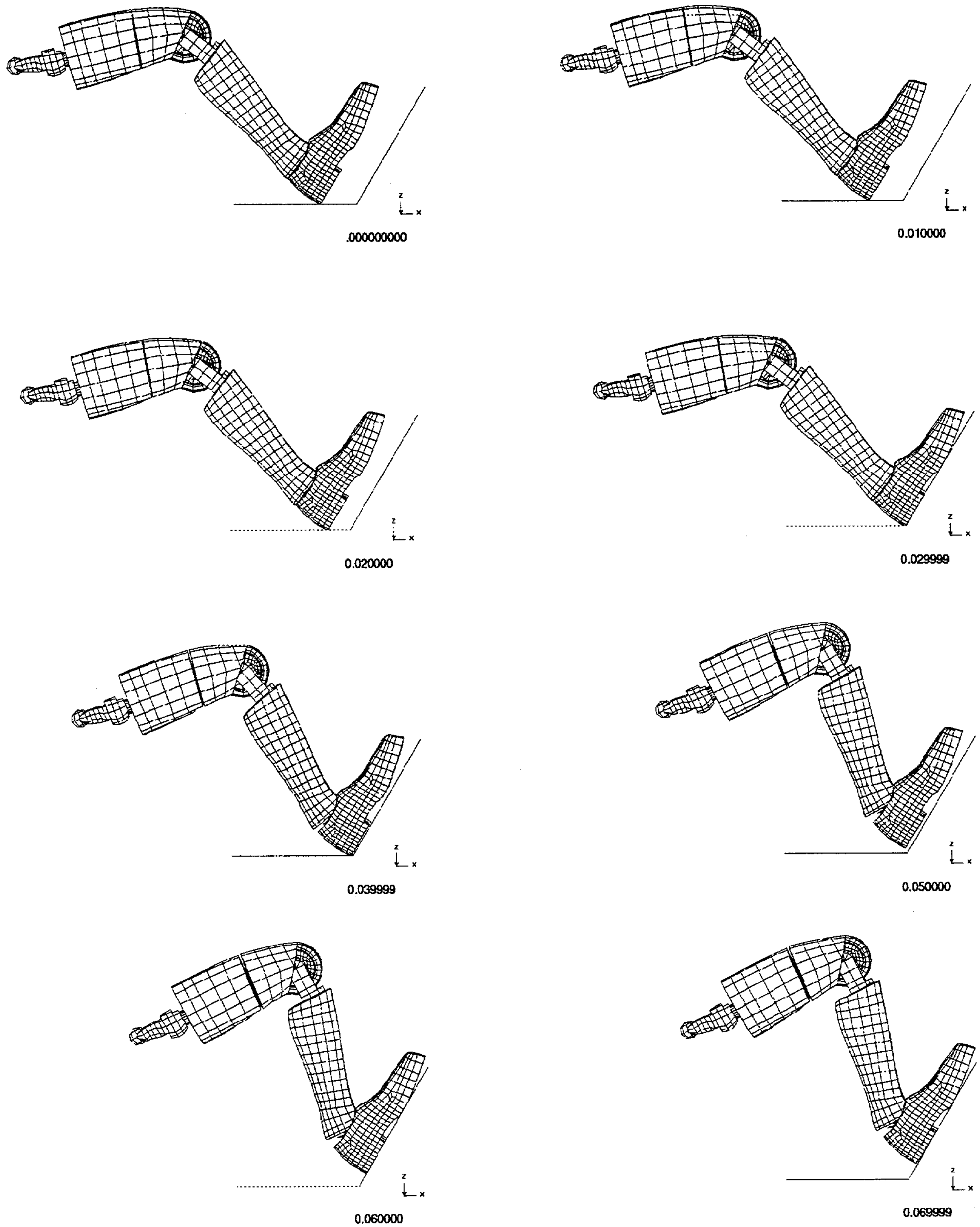

Figure 19: Event sequence for the right leg in HyGe test used for model validation work.