Finite Element Modelling of Biomechanical Dummies- The Ultimate Tool in Anti-Whiplash Safety Design?

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ABSTRACT

Nowadays, people purchasing a new car are no longer simply looking for attractive styling, good performance and an efficient, reliable engine; one of their main concerns is now also the safety of the car. During the last decade, significant progress in improving car occupant safety has been made through the use of safety devices, such as airbags and advanced seat belts, as well as the construction of the car body itself. However, much still needs to be done to satisfy increasingly stringent legislation and public demand.

This work deals with the problem of whiplash injuries that traditionally, due to difficulties in diagnosis, have been very difficult to investigate let alone prevent. Nevertheless, some progress has recently been made in this field. We have previously presented a simplified dynamic FE model of the cervical spine which, using comparisons with the latest experimental work on fresh cadavers, allowed the mechanism of injury to be defined. Subsequently the spine model was used in conjunction with a simple occupant model to investigate the possibility of creating a design tool for anti-whiplash devices. This work, although only preliminary, indicated that the approach of grafting a fully biomechanical FE model of the cervical spine onto a conventional FE model of a crash test dummy could produce an unrivalled analysis of a whiplash injury situation.

In the present work a new, more advanced biomechanical FE model of the head–neck complex has been created and combined with the Hybrid III FE dummy model, which is the industry standard tool for occupant safety. The principal modifications are the method of modelling soft tissues and the representation of the inertial properties of the head to achieve a more realistic behaviour of the model.

INTRODUCTION

Cervical “whiplash” is the most common injury sustained in car accidents. In 93.5% of all rear end collisions involving personal injuries, at least one of the passengers claimed a neck injury, even though 70.4% of these accidents occur with speed differences smaller than 15 kph (Institution of German Car Insurers, 1994). Other injuries are comparatively rare (Muenker, 1994) and therefore the incidence of whiplash injuries is significant from both the economical and the medical point of view

Experimental studies of the Mechanism of Injury (MoI) of whiplash are limited by several factors. Volunteer testing is only possible for relatively low impact speeds in order to protect the test person (Geigl, 1994), while the use of Post Mortal Test Objects is morally questionable. Furthermore, there are no means to measure the ligamental strain *in vivo*. Recently an extensive *in vitro* test series has been published by Grauer (1997). This study used selected cervical spines to investigate the MoI, but the requirements of the test the head had to be replaced by a surrogate metal plate. This led to the destruction of the ligamentous structure in the most critical C0-C2 complex.

There have been several FE-models of the cervical spine reported in literature (Kleinberger, 1993;Nitsche, 1996;Yang, 1998), mainly concentrating on the explanation of the injury mechanism. The most common approach uses self-contained models of the cervical spine, sometimes not even including the head, not to mention any detailed representation of the vital C0-C1 complex. That kind of modelling, however significant for explanation of the MoI, could not be used in the full-scale accident simulations necessary for testing new designs. The interaction between the body of the occupant and the seating system is very important.

The automobile industry uses models of crash test dummies for computer simulations, but their biofidelity is questionable. Since biomechanical modelling of the whole occupant body is a very complicated task, the grafting of critical parts of biomechanical models onto more general models of occupants seems to be the only available approach right now. The use of crash test dummy models seems to be the obvious choice for representing the human body in this kind of hybrid modelling since they are an industry standard for safety.

APPROACH

Model Geometry

The model used in the present investigation (Figure 1) consists of a biomechanical head-neck complex combined with the Hybrid III dummy model in a simplified vehicle seat environment.

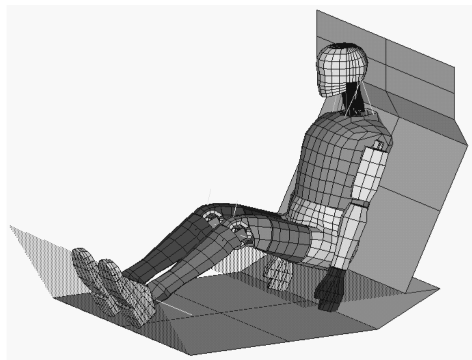

Figure 1. Isometric view of the FEA Model

The new head–neck model was developed using the preliminary model (Golinski, 1999; Heitplatz, 1998) as an overall geometrical reference. The bony structures are modelled using shell elements with the geometry modified to achieve better interaction with soft tissue. All the ligaments of the cervical spine are represented in the model using a mixed structure of shell and non-linear spring elements, except for the Nuchal Ligament, which is modelled with shell elements only. Due to this approach, interaction through the contact interfaces between ligaments and bones was made possible, preserving the non-linear properties of soft tissue. Spring elements are used to model the nine muscles present in the model. The intervertebral discs are represented using solid elements. Symmetry conditions in the head-neck model were assumed along the sagittal plane. The details of the head-neck model are given in Table 1, while the neck part of it can be seen in Figure 2.

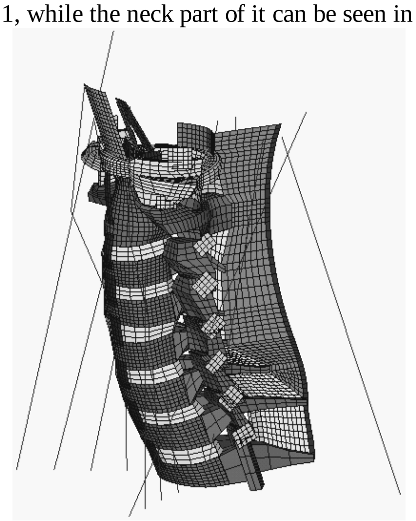

Figure 2. Isometric view of the C1-T1 part of the FEA Model.

The rigidified FE Hybrid III dummy model of a 50^{th} percentile male, supplied with LS-DYNA (LSTC, 1998), has been used in this investigation as a representation of an industry standard for occupant safety engineering. The combined model of the Hybrid III dummy model with the biomechanical head-neck complex was placed in a simple model of a seat environment.

Table 1. Summary of the FE Model Data

Structure	***Type of element***	***No. of elements***
Skull	*ELEMENT_SHELL	1124
Cervical vertebrae	*ELEMENT_SHELL	8268
Discs	*ELEMENT_SOLID	576
Ligaments	*ELEMENT_SHELL	1984
	*ELEMENT_DISCRETE	1891
Muscles	*ELEMENT_DISCRETE	18
Total number of elements		**17011**
(head-neck model only)		**(13861)**
Total number of nodes		**18872**
(head-neck model only)		**(13305)**

Model Properties

The skull and vertebrae were assumed rigid since, according to the accident statistics (Institution of German Car Insurers, 1994), no damage to the bone structure is expected. All the ligaments, except the Nuchal Ligament, were modelled as mixed structures of non-linear discrete tension-only elements and elastic shells. The force/deformation load curves for discrete elements were based on experimental results (Dvorak, 1988; Myklebust, 1988). The shell element stiffness properties were calculated from 1% of the breaking force and the corresponding deflection. The geometrical properties of the ligaments were based on available experimental results (Yoganandan, 1998; Dvorak, 1988; Panjabi, 1991; Przybylski 1998), while properties of the muscular structure were established from test data for the sternocleidomastoid muscles (Yamada, 1970). The discs were modelled with a Blatz-Ko rubber model using a shear modulus of 4 MPa which has been shown to lead to a realistic deformation.

The inertia properties of the head-neck model were implemented using LS-DYNA's PART_INERTIA card.

The head mass and inertia characteristics were taken from a study by Dauvilliers (1994):
M = 4.615 kg; Ixx = 0.0159 kgm^2; Iyy = 0.024 kgm^2; Izz = 0.0221 kgm^2

The position of the head centre of gravity was based on the results of Ewing (1973) and Beier (1980).

The vertebrae inertia properties were taken from the preliminary model (Golinski 1999, Heitplatz 1998).

Table 2 shows a summary of the material properties used for the model of the head-neck complex. For the properties of the body model refer to LSTC (1998).

Table 2. Summary of material properties of the head-neck complex.

Structure	***Material formulation***	***Material Properties***	
Skull	*MAT_RIGID	-	-
Cervical vertebrae	*MAT_RIGID	-	-
Discs	*MAT_BLATZ-KO_RUBBER	G=4	
Nuchal Ligament	*MAT_ELASTIC	E=4.42	ν=0.3
Other Ligaments	*MAT_SPRING_NONLINEAR_ELASTIC	Loadcurve	-
	*MAT_ELASTIC	E~1%LCM	ν=0.3
Muscles	*MAT_SPRING_NONLINEAR_ELASTIC	Loadcurve	-

E = Young's Modulus (MPa); ν = Poisson's Ratio; G =Shear Modulus (MPa);
LCM = Tearing Force of Ligament

Loading Conditions

The loading data for the present study were based on sled experiments conducted by Geigl (1996, CD-Crash Ver. 1.3). To evaluate the model, one of the experiments (MERCEDES 200-300 W 124, 1987 [MB 190] test NR.2) was reconstructed. The recorded test sled acceleration history was used to load the floor of the car, leaving the motion of the seating system with the occupant to be determined by the model.

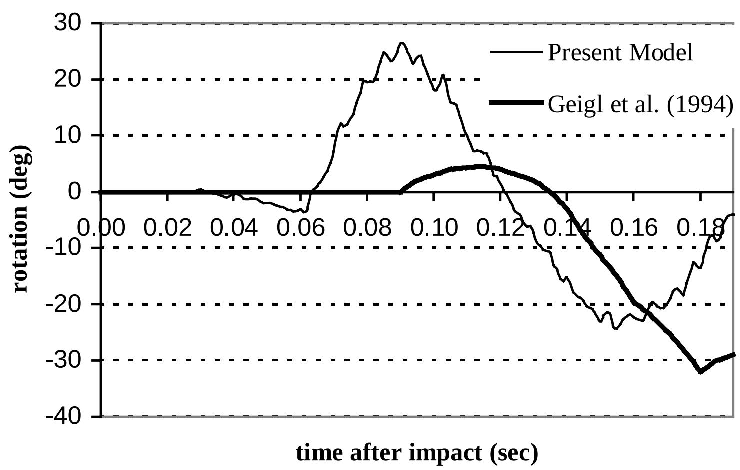

Figure 3. Relative rotation between head and C3 during a 10.5 kph rear end impact, comparing the experimental data of Geigl et al. with the numerical prediction.

A real seat back would deform backwards under the impact with the torso, extending the initial distance between the head and the head restraint delaying the head response and reducing much of the impact. The use of a symbolic seat system in the present model, which does not deform, resulted in moving the impact of the head to an earlier stage in the event and making it more severe (Figure 3). Therefore, in the model under investigation, the rotation of the head starts earlier than in the volunteer experiment. However, the same general movement of the head can be clearly seen. Looking at the difference in the peak values of the rotation, a few issues must be borne in mind. First, the experimental results are based on a movie recorded during the experiments. The reference points for these results (external markers on the volunteer's head and torso) are clearly different from the internal ones used in the simulation. Secondly, the simple model of the occupant body, as well as the simple model of the seat environment used in the simulation, did not satisfy energy conservation as well as the real deformations observed in the experiment. In that light, the performance of the model can be assessed as quite good.

DISCUSSION OF RESULTS

Since the hybrid model uses the dummy body, the first natural comparison is done against the behaviour of the dummy. On Figure 5, the relative rotation of the head to the base of the neck has been shown. As it can be seen, the dummy neck does not even closely resemble the behaviour of the biomechanical neck, which has been validated against experimental data from test with volunteers. Note that due to the dummy neck being a vertical "tube," the head rest for the dummy simulation had to be moved backwards by 52mm to achieve the same initial 80mm gap between the head and the head restraint.

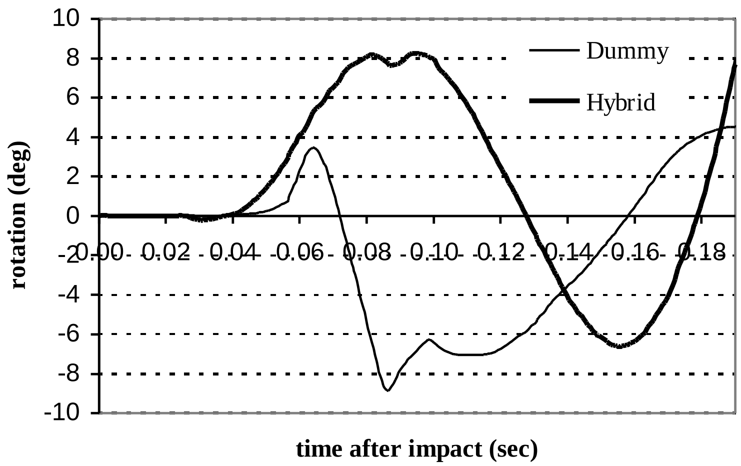

Figure 4: Head rotation relative to the base of the neck.

This result alone is a good recommendation for using the hybrid model for safety design. The dummy on its own is not capable of representing the behaviour of the neck in rear accidents situations and will give misleading results to designers.

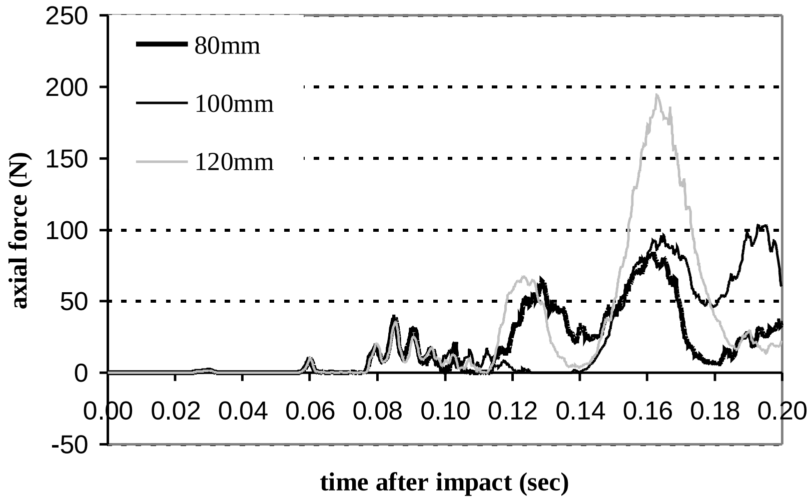

Figure 5 Force/time relationship of the apical ligament.

To show the most important characteristic of the biomechanical neck model, some more solutions with different initial gaps have been calculated. The biomechanical modelling advantage over the common dummy models can be clearly seen on the two following examples of loading on individual ligaments shown in Figures 5 and 6. For example, the loading of the apical ligament increases with the remoteness of the head restraint, implying the need to keep the head restraint as close as possible to the head.

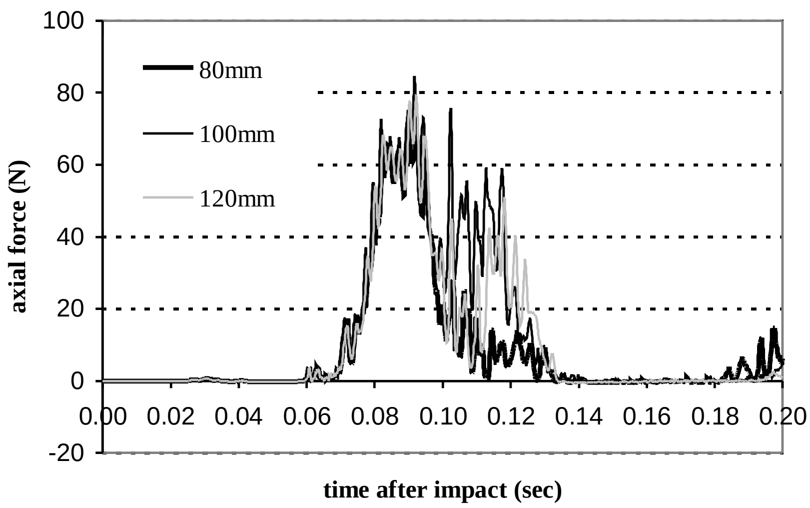

Figure 6 Force/time relationship of the ligamentum flavum.

This kind of data, which can be very valuable for safety design, is not available using crash test dummy models. Based on the results from individual ligaments, present seat designs can be assessed and new anti-whiplash designs can be developed.

CONCLUSION

The work presented describes a new approach to some aspects of car safety design based on biomechanical modelling of the human body. So far, motor industry designs have been based on real tests or Finite Element investigations based on test dummies. While dummies seem to be irreplaceable for real crash tests, there is potential in Finite Element investigations for a biomechanical approach to enhance the safety of car occupants. However, there is still a long way to go to create a full biomechanical model of the human body. The approach presented in this study of combining biomechanical parts with dummy models can be seen as the first step in this process.

The results presented in this work, although preliminary, are strong recommendations for the use of biomechanical modelling in car safety studies. While information such as head rotation and acceleration can already be extracted from existing mechanical dummy models, this approach of using a hybrid model with a fully biomechanical head-neck complex is completely new and gives the first opportunity to investigate the loading in individual ligaments.

During the investigation, the lack of a deformable seat model has been the biggest obstacle to showing the full capabilities of the present model. Therefore, in future investigations it will be necessary to include a more accurate generic model of a deformable seat to use the hybrid dummy model for the project’s overall aim of developing an anti-whiplash device.

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