IDENTIFICATION OF HEAD INJURY MECHANISMS ASSOCIATED WITH RECONSTRUCTION OF TRAFFIC ACCIDENTS.

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ABSTRACT

Head injuries often occur in frontal accidents, which are the most frequent type of vehicle collision and causes of injuries. Impact of the head with the steering wheel has been identified as the major source of lesions. In order to mitigate this contact, vehicles available on the European market are now equipped with airbags in addition to the safety belt. Although the inflation of airbags reduces the severity of head injuries in moderate to severe frontal crashes, lesions due to a contact with the steering wheel are still observed in collisions with a severity under the deployment threshold. The analyses of real-life accidents involving airbag deployments show that additional injuries occur in accidents of relatively slight severity. Accordingly, several authors have proposed to increase the deployment threshold of the airbag system for belted occupants. The absence of head injury representative biomechanical criteria prevents an assessment of the risks induced by such a modification.

Many studies in the past have demonstrated that the current biomechanical criteria (HIC, SI) are meaningless in real accident situations. Despite the fact that the mechanisms causing head injury were unknown, several injury criteria were proposed which were based on hypothetical theories. To obtain a better understanding of head injury mechanisms and propose new biomechanical criteria in the future, a new research methodology has been developed.

The purpose of this study is to present the accident reconstruction methodology so as to provide an estimate of the head loads which are associated with the injuries sustained by the victim. This is however only the preliminary step in the complete analysis. Simulations of head loads with the conditions extracted from the accident reconstruction are the next stage for the identification of head injury mechanisms.

THE ANALYSIS OF ROAD ACCIDENTS registered in France in 1998 shows that they are becoming more and more severe. Whereas the number of accidents is decreasing, there is a marked and dramatic 5.6% increase concerning the number of fatalities in comparison with 1997 statistical data. There are three major concerns about this unfavourable evolution :

- The increase in traffic which reached +4.3% in 1998 when the average for the last ten years is closer to +3.3%.
- The particularly bad weather in January 1997 had a low accidentology. By comparison, the meteorological conditions in January 1998 were better and 177 additional deaths were recorded.
- Although the month of July is generally fatal, an unusual rise (+118) has been noted which is associated with the euphoria of the world cup in football and the French team's victory.

Frontal impacts are the most common type of vehicle collision and cause of injury (Bendjellal et al., 1997). The various statistical data sets of frontal impacts represent more than 60% of the collision configurations (Scheunert et al., 1992). Foret-Bruno et al. reported that frontal collisions account for 70% of severely injured belted front occupants and 48% of fatalities(1994). Occupant injuries are caused by contact with the vehicle interior related to compartment intrusion and by restraining loads due to acceleration. Many researchers have studied the relationship between the overlap amount and the injury probability. According to Hobbs (1991) and Thomas (1994) large intrusions are mainly responsible for severe to fatal injuries MAIS 3+ in frontal collisions. Foret-Bruno et al. (1994) noted that the frequencies of head to steering wheel impact rose significantly with increasing vertical displacement.

Bradford et al. (1986) examined head injuries in car accidents and found that 65% of fatalities had a head injury of AIS 3 to 6. In the same way, Harms et al. (1991) studied the patterns and cause of serious injuries amongst car occupants. He found that in terms of total numbers, head and limb injuries predominated. According to Frampton et al. (1992), the head/face was one of the most frequently injured body regions for restrained drivers and the most frequent when the AIS was greater than 1. When an injury producing contact was identified for head/face injuries, the steering wheel was the component the most frequently struck.

Thomas et al. (1995) studied the head injuries sustained by restrained front seat occupants in frontal collisions and identified the contact with the steering wheel as the most common cause of lesions. He found intrusion to be a crucial factor when head injuries were caused by steering wheel contact. He thought that the most effective technique to mitigate head injuries caused by the steering wheel was probably to avoid contact. Airbags have been suggested as a means of reducing face injuries with the steering wheel.

The airbag has been in use in the United States for several years now but it has only been standard use for some European vehicle manufacturers since the 90s and is meant to be used in conjunction with the seat belt. The effects of the airbag plus the seat belt in real-life accidents can only be studied from real-world crashes in which the airbag has been deployed. The fact that airbag-equipped vehicles have recently been introduced to the European market, means that a relatively small number of cases have been analysed. Although a decrease in the level and the severity of head and face injuries has been observed for belted and airbag-protected drivers involved in severe frontal crashes, additional injuries identified as airbag specific lesions have been reported in the case of moderate crashes. These are some haematoma in the thorax and face region as well as bums and abrasions injuries (Otte 1995 ; Morris et al., 1996).

Otte (1995) found that half of the airbag's inflation caused a distortion of the vertical vertebra and suggested using the airbag in the higher accident severity of ΔV above 35 to 40 km/h. According to Morris et al. (1996), 25% of airbag deployments occurred in collisions with a severity below 25 km/h. As AIS2+ injuries of any sort are comparatively rare at this collision severity, they thought that there were few benefits to be gained from deployment in such circumstances as unnecessary deployments increase insurance costs. Such modifications would probably have a wrong effect on the head injury severities because Thomas et al. (1995) reported that 23% of all head injuries from steering wheel contact occur at ΔV below 30 km/h which is generally the trigger level for Eurobags.

Knowledge of the head injuries mechanisms occuring in these accident conditions may contribute to solve the problem. Unfortunately, the mechanisms causing head injury in real traffic accidents are still not clearly understood. Many studies have been made in the past to explain the ability of individual loads, impacts or accelerations, to cause only one of a few particular head injuries. However, in the case of head impact with the steering wheel, the head is subject to a high force after a high acceleration. The wide variety of head injuries are generally divided into cranial injuries (skull fractures) and intracranial injuries. The intracranial injuries are further subdivided into injuries to vascular and neurological tissues. Gennarelli (1985) noted that skull fracture can occur with or without brain damage, but is in itself not an important cause of neurological injury. On the other hand, Bandak (1996) underlined the fact that serious head injuries, as defined by their relative threat to life, are those generally associated with the brain. The long-term effects of head injuries are also a significant factor since many patients with minor and moderate injury experience chronic headaches and memory loss even months after the accident (Viano 1985).

A new research methodology consisting in traffic accident reconstruction has been developed in order to better understand how automobile crash victims sustain serious head injuries. The purpose of this paper is to present our methodology and summarise the reconstruction of one accident case selected from the Laboratory of Accidentology and Biomechanics data base.

METHODOLOGY

The selection of the accidents to be reconstructed is an important step in the methodology of reconstruction. The information required to reconstruct an accident are the tyre tracks, the breaking-off of elements from the vehicles which indicate the point of impact, the final position of the vehicles involved in the accident, vehicles and scene photographs and accounts by victims or possible witnesses. A location and description of areas impacted by the victim in the vehicle is useful. The information concerning the victims in particular are the description of injuries (injury type, location and severities) on certain parts of the body and MRI or CT scans. Once an accident has been selected, the quality of the reconstruction depends on the data available. The steps in the reconstruction methodology are outlined in Fig. 1.

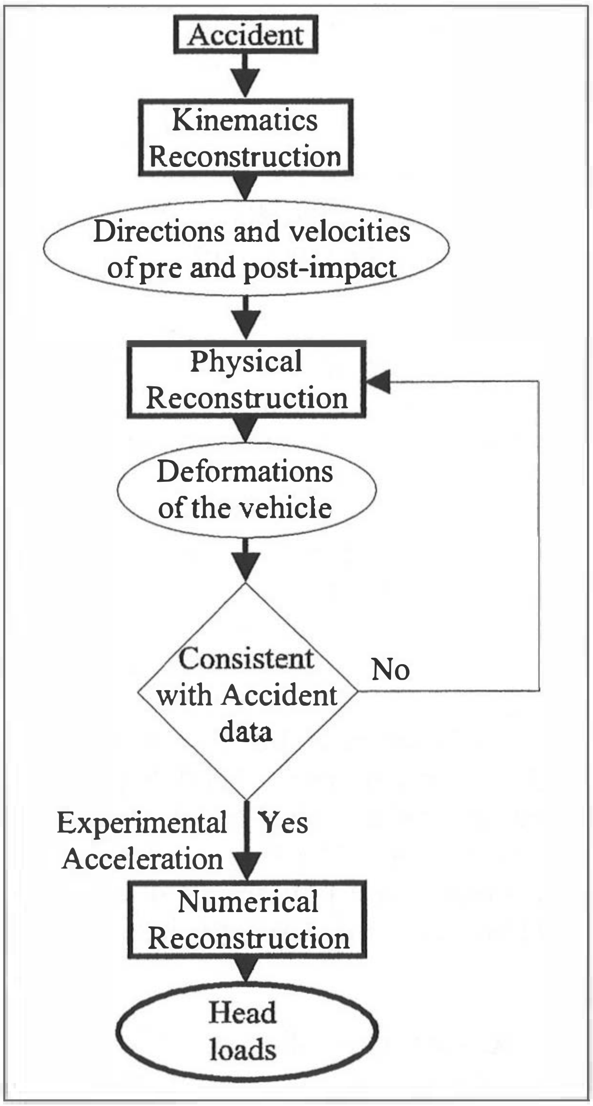

Fig. 1 - Diagram of the methodology

The first step of the methodology concerns the reconstruction kinematics of the accident. The main objectives are to assess the pre and post directions and velocities of the vehicle(s) involved in the accident and the ΔV of the vehicle(s). The ΔV is the change in the velocity of the vehicle's occupant compartment during the collision phase (i.e. from the moment of initial contact between both vehicles or an obstacle until the moment of their separation). According to the principle of conservation of energy, the total energy of the vehicle before the impact is equal to the total of the vehicle energies after the impact plus the energy of deformation. The energy dissipated by the vehicles is expressed by the following equation : $W_d = \frac{1}{2} \cdot M \cdot EES^2$

where **W_d** is the energy dissipated by the vehicle,

M is the mass of the vehicle,

EES is the Equivalent Energy Speed which corresponds to the velocity of a frontal vehicle-to-rigid-barrier impact that will lead to an equal level of frontal deformation as that found in the real accident. To determine the EES value, detailed photographic documentation of various crash tests are compared with that of the accident.

As occupant injuries are caused by contact with the vehicle interior related to compartment intrusion and by restraining loads due to acceleration, a physical reconstruction of the collision of the vehicle studied is undertaken in order to evaluate the deceleration generated in the vehicle's compartment. This experiment can be realised either on a test track with vehicles similar to those involved in the accident or in a catapult with a vehicle impacting against a rigid barrier. In both cases, accelerometers mounted at the left/right B-pillar are used to record the vehicles' decelerations. Unfortunately, deformations of the interior compartment are more difficult to obtain because an accelerometer mounted on the instrument panel will record both the deceleration of the vehicle and the acceleration due to the intrusion of constituents into the interior compartment. Modes of deformation are generally complex since they result in combined rotational and linear motion of the constituents which make experimental measurements complicated. Moreover, as instrument panels are made from plastic, wrong information will probably be observed due to vibrations. The physical reconstruction therefore allows us to verify the results taken from the kinematics' reconstruction and, in the case of a correlation with the accident data, it will give the deceleration of the vehicle.

Although the exterior deformations of the vehicle used for the physical reconstruction can be similar to the final damaged state of the vehicle involved in the accident, intrusion and interior deformations can be different. Several reasons can be put forward. As the deformations of the vehicle end's structure include a succession of car components' deformations, slight differences in each part can finally lead to a deformation mechanism of the vehicle which is different to that observed in the real accident and therefore modify the intrusion into the vehicle's compartment. Moreover the position of the seat and the angle of the back are estimated and the mechanical dummy used for the physical reconstruction does not represent the human victim exactly. The increase in uncertainties can finally result in an erroneous measure of the head loads.

The use of a multibody model representing the second collision (impact between the dummy and the interior constituents of the vehicle) allows us to rectify the differences in deformations between the vehicle involved in the accident and the one used for the physical reconstruction. The model consists of a car with a deforming compartment and a Hybrid III dummy. The model is made up of a rigid body representing the chassis connected to the inertial space by a planar joint and a collection of bodies linked together with joints. It comprises some key interior surfaces such as the seat, a three point belt system, an instrument panel, a windshield and a steering wheel.

In the numerical model we consider that external loads do not induce any structural deformation. Instead, prescribed motions for the bodies representing the constituent of the passenger compartment model the intrusion into the vehicle. Motion data is derived from an interpolation made from the initial undeformed state to the final deformed state of the vehicle involved in the accident.

The vehicle and the dummy are animated with the initial velocity recorded during the physical reconstruction. The former is decelerated by the acceleration data acquired from the experimental test and the prescribed motions are imposed on the bodies representing the structure of the passenger compartment in order to model the intrusion. The simulation with the multibody model allows us to identify the linear and rotational accelerations and velocities of the victim's head, the impact forces applied to the head and values for the Head Injury Criterion (HIC).

ACCIDENT CASE FOR RECONSTRUCTION

In order to illustrate the reconstruction methodology, a specific case will be discussed. The aim of this pilot study was to prove the feasibility of the analysis and to illustrate the types of benefits available from this analysis technique, rather than to produce a definitive description of the head loads and associated injuries in accidents. Most of the characteristics used for the multibody model are extracted from values found in the literature. When we will put the methodology into practice, experimental characterisations will be undertaken for all components used in the multibody model.

The accident involved an offset frontal collision of a Renault 9 vehicle against a tree. The road was slippery because there was thick mud. The driver lost control of her vehicle and impacted a tree on the other side of the road. A sketch plan of the accident is presented in Fig. 2. The diameter of the tree is 0.83m.

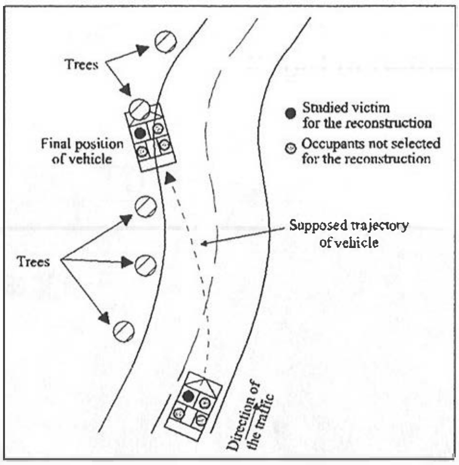

Fig. 2 - Sketch plan of the accident conditions

The four occupants were badly injured and particularly the female driver, 38 years old, who sustained injuries to her head, chest, pelvis and lower limbs. This victim is the one selected for our study. She measured 1.63m and weighed 60 Kg. She was restrained by a conventional 3-point belt with a retractor. The most serious injuries were rated as AIS 5 (head), according to the Abbreviated Injury Scale rating system. The head injuries included a five weeks period of unconsciousness (AIS 5), a permanent dilatation of the left pupil (mydriase) and a cerebral haemorrhage contusion of the right nucleus caudatus (vascular injury) (AIS 4). The victim sustained profound traces of the belt on her chest (AIS 1). Injuries to the pelvis included skin abrasion in regard to the iliac crest due to the belt (AIS 1). The victim also sustained a skin abrasion of the right ankle (AIS 1). She was hospitalised for a period of twelve months.

The female front seat passenger, 21 years old, sustained neck pain (AIS 1), a thorax skin abrasion due to the belt (AIS 1), a skin abrasion on the left hip due to the belt (AIS 1) and a skin abrasion of the left shinbone. The female child, 7 years old, sitting in the left rear place sustained an abrasion on her left groin (AIS 1), an abdominal contusion (left hemoperitoine) (AIS 2), a liver laceration (AIS 2), a left retroperitoneum hematoma (AIS 3) and a contusion of the left kidney (AIS 3). The female child, 3 ½ years old, sitting in the right rear place sustained an abrasion on her left groin due to the belt (AIS 1), an abrasion on the left knee, probably due to the impact on the front seat back (AIS 1), a major laceration of the spleen (AIS 4) and a laceration of the pancreas (AIS 2).

The physical reconstruction was carried out against a rigid barrier. A 0.83m diameter steel cylinder was filled with concrete and fixed onto the barrier. The cylinder represented the cylindrical form of the tree. A Renault 9 vehicle similar to the one in the accident was used. One Hybrid III 5th percentile dummy was put in the driver's seat. The vehicle was equipped with accelerometers at the right and left B-pillar. The impact point was at the front of the car on the left. The measured speed of the car against the rigid wall was 51.5 km/h, an average of the estimated Equivalent Energy Speed. The comparison of both damaged vehicles is presented in Fig. 3.

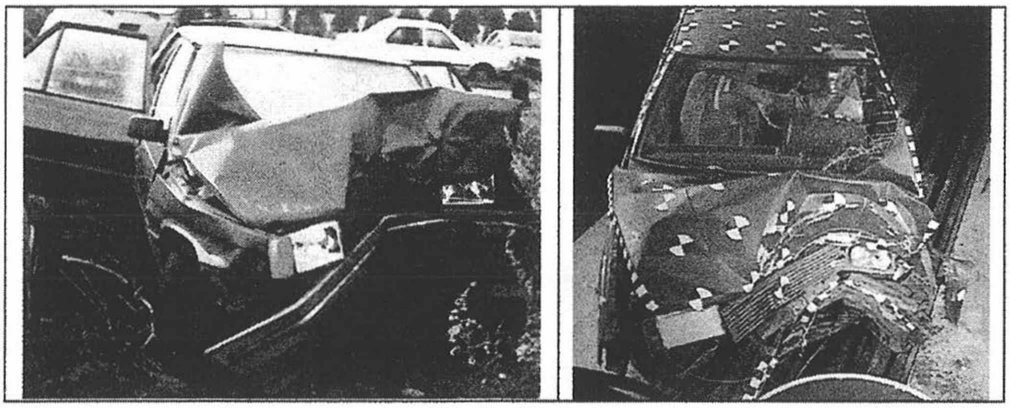

Fig. 3 - Comparison of both damaged vehicles

The deformations observed in the physical reconstruction were measured and they were found to correlate significantly with those of the vehicle involved in the accident in order for us to accept the physical reconstruction representative of the accident conditions. The deceleration recorded during the reconstruction will be used for the multibody model. The linear accelerations taken from the physical reconstruction are given in Fig. 4.

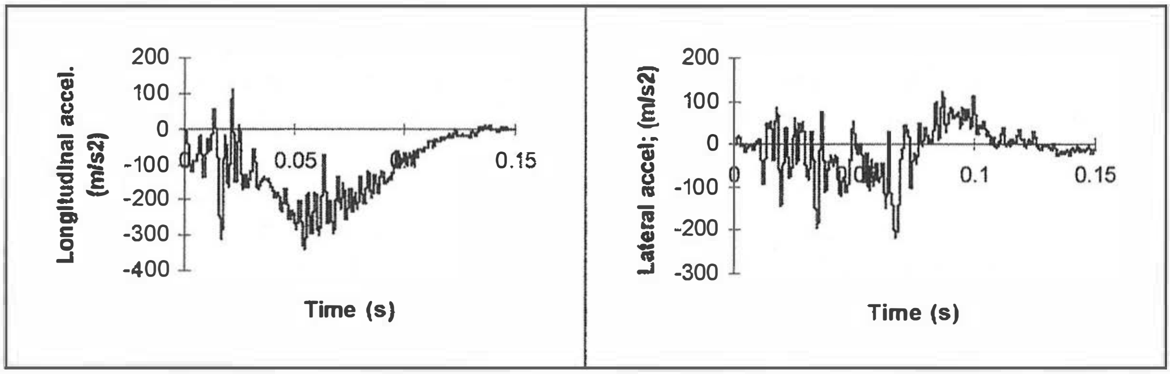

Fig. 4 - Experimental accelerations used for the multibody model

A multibody model representing the second collision was carried out afterwards. Figure 5 illustrates the model containing a hybrid III 5th percentile dummy restrained by a conventional 3 point belt with a retractor sitting in a model of the vehicle. The origin of the vehicle's co-ordinate system is placed in the middle of both left/right B-pillar. The co-ordinate system is oriented such that the X-axis points forward, the Y-axis leftward and the Z-axis upwards. In the numerical model we consider that the structural deformations are not induced by any external loads. Instead, motion data is used to model the structural deformations directly. In order to determine the motion of the corresponding bodies, an interpolation is made from the undeformed to the deformed state of the vehicle involved in the accident. The vehicle is modelled as a collection of bodies linked together with joints. The location and type of these joints are determined according to the deformations observed on the vehicle involved in the accident.

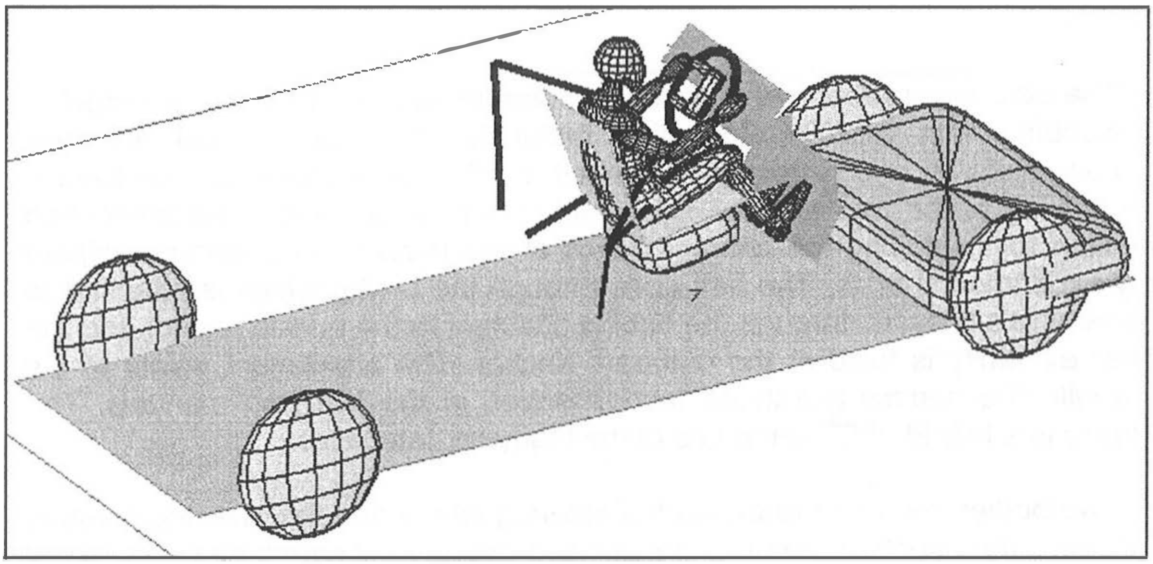

Fig. 5 - Multibody model of the second collision

During the collision, the X-axis accelerometer cable was cut off. The data was recorded 20 ms after the initial time of the collision and only the accelerations of the Y and Z-axis were available, as shown in Figure 6. This particular problem does not allow us to compare numerical and experimental accelerations of the head. As only one accelerometer was mounted in the dummy's head, the numerical acceleration could not be compared with experimental data.

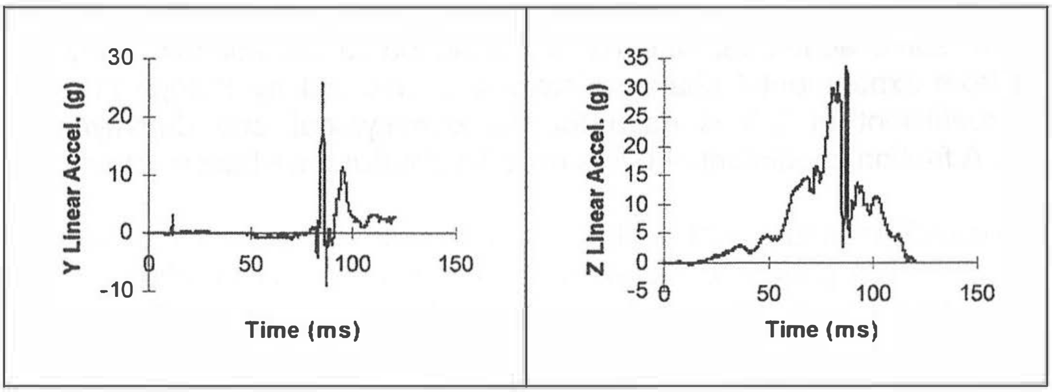

Fig. 6 - Experimental accelerations recorded for the head

The model represents the main components which play a role during the collision. It consists of the chassis, the toeboard, the dashboard, the windscreen, the seat cushion, the seat back, the low and middle instrument panel. The mass measured on the physical reconstruction's vehicle was included in the model. Inertia was calculated with the Burg and Steffan formulations (MacInnis 1997). The vehicle and the dummy are initially animated with the velocity of the vehicle measured during the physical reconstruction. The vehicle is then decelerated by the acceleration taken from the physical reconstruction. An estimated rotational acceleration is also applied to the vehicle.

The belt system represents a conventional three point-belt with a retractor. A webbing with a 10% elongation factor is used for the belt stiffness characteristic. At one extremity of the belt, a retractor model allows us to take the locking of the reel and the film spool effect into account. The prescribed function for modelling the characteristics of the retractor is assessed without any experimental tests. The belt goes through the D-ring which is attached to the vehicle's chassis, through the buckle attached to the buckle anchor and the other extremity is fixed at the outboard anchor. The attachment points of the belt with the dummy are those recommended in the Madymo manuals. The dummy is a hybrid III 5th percentile of the Madymo database.

Two bodies are used to model the steering wheel and the steering column. The body representing the steering wheel is defined according to the shape of the vehicle's steering wheel. Nineteen ellipsoids are used, one representing the hub, two others the branches and the sixteen others the rim. The base of the steering column is connected to the rest of the vehicle by a planar joint. This joint allows longitudinal and lateral movements and rotation around the vertical axis. A translational joint between the steering column and the steering wheel is also used in order to impose three translations and a rotation to the steering system. The degrees of freedom are prescribed with motion data representing the intrusion of the steering wheel into the vehicle compartment.

Contacts are assigned to describe vehicle/dummy interactions. As the stiffness of all parts of the dummy are not prescribed in the Madymo dummies data base, some additional stiffnesses are added to the dummy. They were derived from experimental characterisations carried out by Kaleps (1988). A friction coefficient of 0.3 is used for the dummy/seat and dummy/interior contacts. A friction coefficient of 0.8 is used for the dummy/chassis interactions.

The simulation time is set to 140 ms. Intrusion is imposed from 40ms to 90ms because this period corresponds to the maximum acceleration recorded during the physical reconstruction. A rearward displacement of 8cm, a right lateral displacement of 9cm and an upward displacement of 11cm are imposed on the steering wheel. A rearward displacement of 26.5cm is imposed on the toeboard. This data corresponds to deformations measured in the vehicle involved in the accident. Figure 7 shows the position of the dummy at 80 milliseconds after the beginning of the crash. This instant coincides with the time of impact between the head and the steering wheel. These results are in agreement with medical data and impact points taken from the vehicle involved in the accident. The medical data revealed a direct impact in the left eye area and the plastic constituent covering the hub was broken in three parts. The calculated HIC is 1219,9. Figure 8 represents the most important linear and rotational accelerations expressed at the centre of gravity of the head in the global co-ordinates system and the impact force between the head and the steering wheel hub. All results are unfiltered.

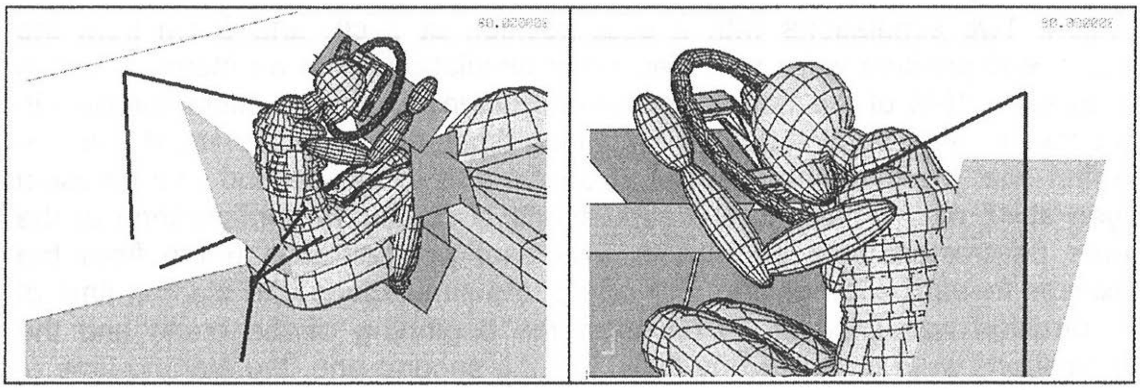

Fig. 7 - Instant of impact between the head and the steering wheel

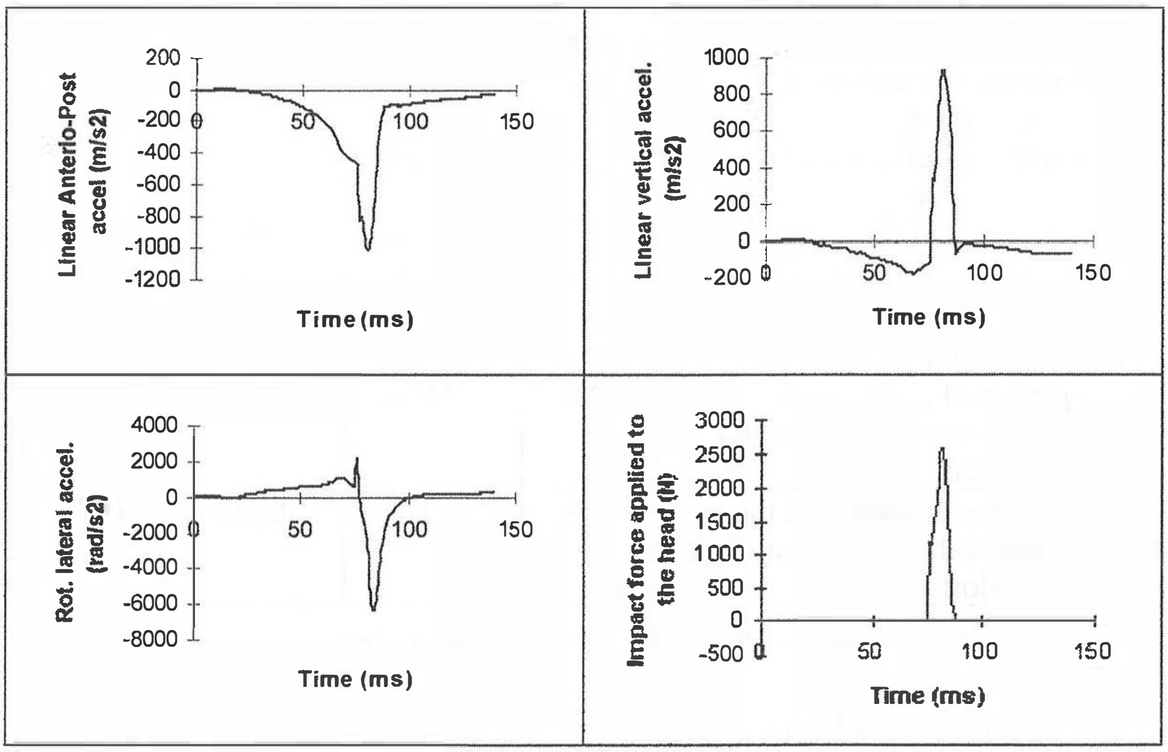

Fig. 8 - Numerical head loads

The results obtained for this pilot analysis confirm what might be expected to happen during the accident and give a head loads estimation. This methodology requires an experimental reconstruction in order to identify the deceleration of the vehicle. By experimentally identifying the component of the vehicle (webbing characteristics, retractor behaviour, instrument panel stiffness ...) the multibody model will allow us to calculate the head loads during the accident. The seat position of the victim is not however always measured because rescue people sometimes need to move or remove the seat. Moreover, vehicles' deformations are difficult to measure exactly. This is why uncertainties concerning this value must be taken into account. Eight simulations were performed. The first two concerned the seat position. In the model presented earlier, the driver's seat was put in the maximum forward position. Two simulations with a seat position at 3 cm and 6 cm from the forward end position were run. Two other simulations with an increase and a decrease of 10% of the final deformations taken from the vehicle involved in the accident were analysed. Two beginning times of intrusion were studied. In the first one, the intrusion was set at 35 ms and in the second one intrusion began at 45 ms. In the last two simulations, a combined configuration of the former parameters was performed. The seat position was 6 cm from the maximum forward end position. For one of the simulations, the starting time of the intrusion was fixed at 45 ms after the beginning of the crash and the deformations were increased by 10%. For the second one, the starting time of the intrusion was put at 35 ms and deformations decreased by 10%.

	Rot accel (y axis)	Lin. Accel (X-axis)	Lin. Accel (Z-axis)	Impact Force
3 cm rearward position of the seat	+2%	+11.1%	+7.3%	+10.1%
6 cm rearward position of the seat	+7.7%	+11.6%	+10.3%	+7.1%
motion data plus 10%	+3.9%	+4.5%	1.8%	+1.2%
motion data less 10%	-4.9%	-6.1%	+3.3%	-3.6%
starting motion (5ms before)	0%	-5.8%	+1.2%	+0.5%
starting motion (5ms after)	-2.4%	+2.5%	-5.6%	-5%
6 cm rearward position of the seat, motion data +10%, starting motion : 45ms	+4.1%	+0.6%	+4.4%	+4.2%
6 cm rearward position of the seat, motion data -10%, starting motion : 35ms	-8.9%	-4.1%	-8.3%	-9.9%

Tab. 1 - influence of the uncertain parameters

The comparison of the peak values for the eight configurations are summarised in Table 1. The general trend of the curves is similar. The most sensitive parameters of the models seemed to be the position of the seat. However, an error of 6cm on the seat's position, which seemed to be a reasonable tolerance, generated a maximum of 11.6% error in the linear acceleration of the head expressed in the anterior-posterior direction. The variation of the starting intrusion time and the decrease or respective increase of motion data representing the intrusion into the interior compartment did not significantly influence the peak values. As for the multiplication of uncertainties in one multibody model (case 7 and 8) the maximum difference concerned the peak of the impact force between the head and the hub of the steering wheel (-9.9%).

This parameter analysis proved that the modification on the position of the seat and the motion data of the steering wheel does not radically alter the head loads. In fact, the motion data imposed on the multibody model slightly modifies the velocity of the steering wheel when it impacts with the head of the dummy, and consequently modifies slightly the head loads of the dummy. These results show the possibility of using this methodology to reconstruct accidents and identify head loads which might be expected to happen during the accident. A simulation with a finite element model of the head of many cases studied may lead to the understanding of head injury mechanisms and finally to head tolerance.

CONCLUSIONS

Head injuries are known to be frequent and severe. However, because of the limitations of biomechanical knowledge, the assessment of the protection offered by a new vehicle model is based on biomechanical criteria which are meaningless in real-world accidents. Although the use of airbags in conjunction with a belt reduces the severity of head injuries in automotive accidents, problems still remain concerning the values of the triggering threshold. To contribute to the development of a new biomechanical criteria of the head, a new research methodology has been envisaged and can be resumed as follows. A physical reconstruction is carried out from the results of the kinematics reconstruction. The physical reconstruction allows us to identify the accelerations applied to the vehicle. These accelerations are then applied to a multibody model representing the second collision. According to the deformation observed on the vehicle involved in the accident, the intrusion of constituents into the interior compartment is established and applied to this model. Results of the simulation give the head loads.

The application of the methodology on a real-world accident allows us to associate head loads and head injuries suffered by the victims. The computed head loads will be applied at the next stage to a 3D finite element model of the head to identify injury mechanisms.

A typical road accident involving head injury to a restrained driver is reconstructed using the previous methodology. The accelerations taken from the physical reconstruction are used as input for the multibody model. The results of the simulation performed confirm what might be expected to happen according to the impact points of the vehicle involved in the accident and medical data of the victim.

In this pilot study, most of the characteristics of the vehicle components of the multibody model were found in the literature but in the future, with experimental tests of all constituents of the vehicle playing a role in the kinematics of the victim, head loads could be accurately evaluated. A parameter analysis shows that uncertainties concerning the seat position and the motion representing the intrusion into the interior compartment do not modify the trend of head loads, only peak values are slightly different. The methodology can finally be applied to traffic accidents. The multiplication of accident cases for reconstruction might lead to the development of a data base "head loads - generated injuries".

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REFERENCES

Bandak F.A. Biomechanics of impact traumatic brain injury. Proceedings of the NATO-ASI on Crashworthiness of Transportation Systems, Structural impact and occupant protection, July 7-19 1996, Troia, Portugal, pp 213-253.

Bendjellal F., Walfisch G., Steyer C., Ventre Ph., Foret-Bruno J.Y., Troseille X. and Lassau J.P. The programmed restraint system – A lesson from accidentology. SAE Paper N° 973333, pp 3765-3779.

Bradford M.A., Otubushin A., Thomas P. and Robertson N.K.B. Head and face injuries to car occupants in accidents. IRCOBI 1986, pp 85-103.

Foret-Bruno J.Y., Le Coz J.Y., Thomas C. and Brutel G. In depth analysis of frontal collisions as regards the influence of overlap and intrusion on occupant severe and fatal injuries. Proc. ESV Conference 94-S4-O-21,1994, pp 676-683.

Frampton R.J., Mackay G.M. and Parkin S. An assessment of real world steering wheel intrusion characteristics and their implications for head and face injuries to restrained drivers in frontal impacts. IRCOBI 1992, pp 373-383

Gennarelli T.A. The state of the art of head injury biomechanics - A review. Twenty-ninth Conference of the American Association for Automotive Medicine, pp 447-463.

Harms P.L. and Tunbridge R.J. Patterns and causes of serious injury amongst car occupants. Proc. ESV Conference 91-S1-W-16, 1991, pp 121-135.

Hobbs C.A. The need for improved structural integrity in frontal car impacts. Proc. ESV Conference 91-S9-O-12, 1991, pp 1073-1079.

Kaleps Richard P., White J. R., Robert M., Boecher, Jennifer Whitestone, Wright-Patterson. Measurement of Hybrid III dummy properties and analytical simulation data base development", AFB OH 45433-6573, 1988.

MacInnis Duane D., Cliff William E., Ising Kurt W. A comparison of moment of inertia estimation techniques for vehicle dynamics simulation. SAE Paper No. 970951, pp 99-116, 1997.

Morris A.P., Thomas P., Brett M., Foret-Bruno J.Y., Thomas C., Otte D. and Ono K. A review of driver airbag deployments in Europe and Japan to date. Proc. ESV Conference 96-S1-O-03, 1996, pp 122-131.

Otte D. Review of the air bag effectiveness in real life accidents demands- for positioning and optimal deployment of air bag systems. SAE Paper N°952701, 1995; pp 1-10.

Scheunert D., Justen R., Herrmann R., Zeidler F., Decker J. and Kallina I. What is a realistic frontal offset test procedure. IRCOBI 1992, pp 75-87.

Thomas P. Real world collisions and appropriate barrier tests. Proc. ESV Conference 94-S8-W-19, 1994, pp 1450-1460.

Thomas P. and Bradford M. The nature and source of the head injuries sustained by restrained front-seat car occupants in frontal collisions. Accid. Anal. and Prev., Vol. 27, N°4, 1995, pp 561-570.

Viano DC. Perspectives on head injury research. IRCOBI 1985, pp 159-176.