HUMAN FACE RESPONSE AT AN ANGLE TO THE FORE-AFT VERTICAL PLANE IMPACT

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ABSTRACT

The stiffness characteristics and the kinematics response of the face of human cadaver are reported. Impact tests with human specimens are necessary to study the biomechanical response to impact, injury mechanisms and injury criteria. To complete existing test data, both INRETS-LBMC and the University of Heidelberg (UNH) performed impact tests on human cadavers.

This work, mainly funded by the European Commission (EC), is part of the task 2.1, of the ADRIA programme (Advanced crash Dummy Research for Injury Assessment in frontal test conditions).

About sixty (including twenty-four funded by the EC) impact tests were performed on fifteen cadavers by INRETS-LBMC. The impacts were delivered by an impactor simulating a steering wheel rim, to the forehead and to the upper maxilla at an angle to the fore-aft vertical (sagittal) plane in order to represent typical accident conditions. The UNH carried out a total of eight tests on four cadavers (funded by the EC). Each cadaver received a padded impact on the left face side and a rigid impact on the right face side.

The head kinematics were recorded by high speed film, and the force and the acceleration of the impactor were measured. This paper presents the results of human cadaver tests, including test conditions and sustained injuries, linear and angular acceleration-time histories, force-time histories, kinematics analysis, injury mechanics and medical findings.

THE INCREASING USAGE OF IMPROVED RESTRAINT SYSTEMS has reduced the occurrence of severe head injuries. Instead, a pattern of less severe facial injuries has emerged, e.g. injuries due to the facial airbag contact. During impacts involving cars, the human face is especially solicited. By its crushing, it absorbs some energy and limits the load transmitted to the skull and brain.

The general objective of the ADRIA European research programme (N° PL96-1074) is to reduce casualties in the Community among vehicle occupants in the most hazardous accident type : frontal collisions. The assessment of the protection offered by a vehicle model is based on biomechanical criteria to be measured on a crash dummy. For this purpose, the most widely used crash dummy today (i.e. the Hybrid III dummy) and the corresponding biomechanical criteria have been proposed for the new European regulation. However, the Hybrid III dummy was developed in the United States in the seventies and it presents a certain number of important limitations, in particular with respect to the injury assessment capabilities for head, face and lower leg injuries.

Some of the objectives of the whole ADRIA project are : 1) to recommend a design of a biofidelic crash dummy face, enabling facial injury assessment in frontal collisions, and 2) to evaluate the current and often criticized Head Injury Criterion (HIC).

The objectives of task 2 are : 1) to enhance the biomechanical knowledge of the dynamic response of the face under impact conditions, 2) to obtain a better understanding of facial injury mechanisms and facial injury criteria, 3) to evaluate the three most promising dummy faces with respect to bio-fidelity and injury assessment capability, and 4) to establish design guidelines for a biofidelic dummy face.

This task 2 is divided into two activities : activity 2.1 addresses the first two objectives. Activity 2.2 addresses the last two objectives. The partners in this task are : TRL (GB), INRETS-LBMC (F), UNH (D), and TNO (NL).

This paper focuses on activity 2.1 and concerned Heidelberg tests and INRETS-LBMC tests.

MATERIAL AND METHODS - The University of Heidelberg (UNH) carried out a total of eight tests (5.1-5.8) on four cadavers. Fifty-seven impact tests (including twenty-four funded by the EC) were performed on fifteen cadavers by INRETS-LBMC (FCA01-57). Table 1 summarizes the main anthropometric data for the cadavers.

Pre-test preparation of the subject - The anthropometric data of the head were documented. The anatomical landmarks defining the Frankfort plane, infraorbital notches and auditory meati were marked with small lead balls. The position of these landmarks were documented by lateral radiography. Based on the X-ray photographs the distances of the top of the head and the occipital condyles to the centre of gravity were defined. The centre of gravity was globally defined according to the results of Beier et al, 1980, with a distance to the Frankfort plane of 8.3 mm in x-direction and -3.12 cm in z-direction. A cervical collar was used in order to hold the head in good position before the impact.

Table 1 : Test matrix with important anthropometric data

Test N°	Sex	Age [years]	Body mass [kg]	Body height [cm]	Head mass [kg]
5.1/5.2	M	57	57	180	3.4
5.3/5.4	M	73	46	160	3.6
5.5/5.6	F	58	39	158	3.1
5.7/5.8	M	45	80	169	4.6
FCA 01 02 03 04	F	73	53.5	1.62	2.90
FCA 05 06 07 08	F	76	66.0	1.80	3.30
FCA 09 10 11 12	M	63	46.0	1.57	4.44
FCA 13 14 15 16	M	64	54.5	1.76	5.14
FCA 17 18 19 20	F	53	78.0	1.64	3.00
FCA 21 22 23 24	F	93	43.0	1.57	3.50
FCA 25 26 27 28	M	84	42.0	1.60	3.77
FCA 29 30 31 32	M	77	67.5	1.75	4.58
FCA 33 34 35	M	72	82.0	1.81	3.75
FCA 36 37 38	M	66	59.0	1.73	3.54
FCA 39 40 41 42	M	65	66.0	1.64	4.60
FCA 43 44 45 46	M	69	56.0	1.80	4.67
FCA 47 48 49 50	M	71	71.0	1.69	3.95
FCA 51 52 53 54	F	71	40.0	1.52	3.14
FCA 55 56 57	F	70	52.0	1.50	3.75

Remark : 5.1 to 5.8 Heidelberg tests, FCA01 to FCA57 INRETS tests

Impact conditions - The tests 5.1 to 5.8 were performed using a linear piston pneumatic impactor. The impacting surface was a flat rigid aluminium plate, 15 cm in diameter. In order to attenuate the head impact energy and to distribute the impact forces, a 40 mm thick polyurethane foam was used (density 165 g/dm^3, standard dashboard padding material). The force-deflection characteristic of the padding material is shown in figure 1. The impactor mass amounts to 23 kg.

For the tests 5.1 to 5.8, the first impact was padded and applied to the left part of the face with an impact direction of 45 degrees. The second one was rigid at the right side of the face with the same impact direction. The same cadaver was used for both impacts (i. e. for each cadaver a padded impact on the left face side and a rigid impact on the right face side).

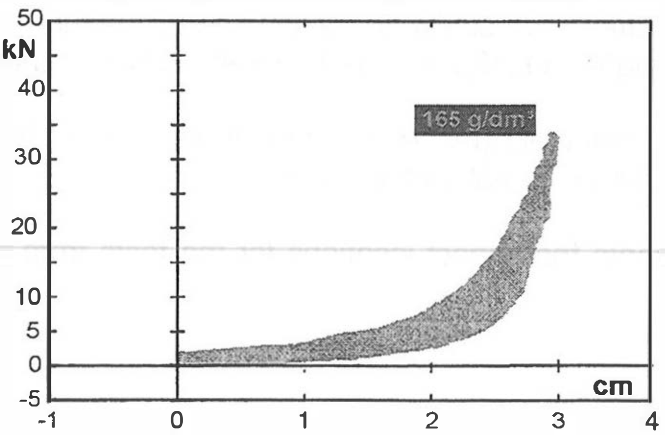

Figure 1 : Dynamic Force-Deflection characteristic of the padding material used

For the tests FCA01 to FCA57, the impacts were delivered by a guided linear impactor simulating a steering wheel rim, to the forehead, the zygomatic bone and the mandible at an angle to the fore-aft vertical plane in order to represent typical accident conditions (Ramet et al, 1994). A 2.25 cm diameter steel cylinder is mounted horizontally at the far extremity of the impactor and hits the face directly. This cylinder represents only the shape of a steering wheel : in fact, the elasticity of the material (steel) is not taken into account. The weight of the impacting mass is 17 kg, except for tests FCA51 to FCA57, for which it is 17.60 kg.

Many reasons led to reproduce the shape of the steering wheel : Thomas et al study (1991) shows that 29 % of the face injuries due to the steering wheel are quite serious ; moreover, just the rim of the steering wheel is responsible of injuries caused by steering wheels in 70 % of the cases.

During a frontal collision between two vehicles, the impacts which are generally applied to the face and to head are often oblique with regard to the fore-aft vertical plane. They can be impacted against a side element of the interior : for example, the lateral superior A-pillar ; or an element facing the driver (steering wheel, dashboard...), preceded by a rotation of the body, due to the restraint of the 3-point belt.

In order to better reproduce the test conditions, the face was angled at 30° with regard to the fore-aft vertical plane.

First of all, it was decided to do tests on a bone of the skull : the forehead (frontal bone). Statistics show that this bone is the most frequently involved in frontal collisions (30% of the facial injuries according to the study of Yamasaki et al, 1994).

Then, tests were carried out under similar impact conditions on the zygomatic bone (malar bone), in order to emphasize the energy absorption by the bones of the head. The zygomatic bone is statistically often affected during frontal collisions (17 % of face injuries).

The impacted areas are similar to those used by Nahum et al, 1968, on the zygomatic bone (right and left), and on the forehead bones (right and left).

Moreover, the mandible (maxilla bone) was also tested in order to see the reaction of the superior dental arch to impact.

Figure 2 presents the impact locations for the tests from FCA01 to FCA57 carried out at INRETS.

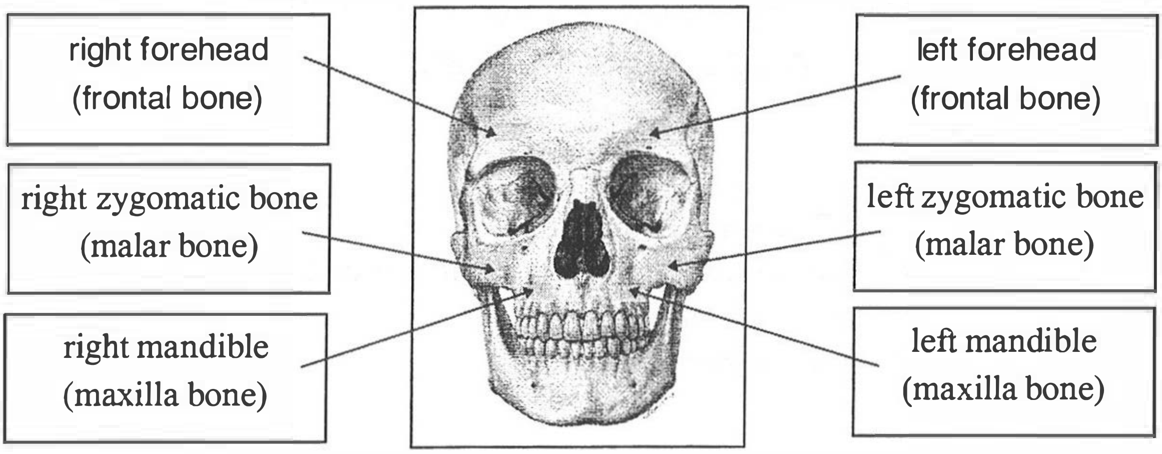

Figure 2 : Impact locations for the tests FCA

Instrumentation - For the test 5.1 to 5.8, the instrumentation of the impactor included a force and acceleration measurement ; the force transducer (piezoelectric) was mounted between the impactor axis and the aluminium plate, while the accelerometer was fixed at the rear of the plate. The head was instrumented with a 9-accelerometer module, as described by Padgaonkar et al (1976), which was attached to the top of the skull. The accelerometers used were of the Endevco 2264-2000 type and were fixed at the accelerating plate at the rear end of the impactor. The location of the 9-accelerometer array with respect to the head centre of gravity and occipital condyles was measured in the lateral X-ray view.

The data were recorded in analog format, and digitized at 10,000 samples per second. The data of the 9-accelerometer array were digitally filtered with CFC 60 and the linear acceleration resultant of the head centre of gravity, the angular velocities and accelerations, the forces and the moments at the level of the occipital condyles were calculated according to Padgaonkar et al (1976) method. The Padgaonkar method is based on a frontal impact. The face was impacted from 45° and this had to be taken into account by an appropriate coordinate transformation. The neck forces were evaluated as the product of the resultant acceleration at the head c.g. and the head mass.

The head mass was calculated according to the following formula :

head mass [kg] =
0.1744 * hat size [cm] - 0.0031 * occ.- chin circumference [cm] - 5.298

This formula is empirical and results from experiences of weighted heads (Wismans et al, 1987) and comparison with results published by Beier et al, 1980.

The neck moments were calculated according to the following formula :

$$\vec{M} = \vec{F} \times \vec{\rho}_{oc} + \theta \cdot \dot{\vec{\varpi}} + \vec{\varpi} \cdot \theta \cdot \vec{\omega}$$

with

$\vec{F}$ – *Force cg*

$\vec{\rho}_{oc}$ – *Position oc relative to cg*

θ – *Moment of inertia (diagonal tensor of 2. order)*

$\vec{\varpi}$ – *angular velocity*

$\dot{\vec{\varpi}}$ – *angular acceleration*

For the tests FCA01 to FCA57, to get reliable measurements, regardless of body dimensions, a tool was needed to recalculate acceleration at the head's centre of gravity. Adapting the sensors directly to different head shapes, might give bad results because each head has its own morphology (dimension, shape...).

So, a light metallic helmet (figure 3) was designed, on which 12 monoaxis accelerometric sensors were positioned, distributed in 4 groups of 3 (one for each direction of the helmet frame). In this way, there are 4 measuring points on the helmet. These 4 measuring points are distributed on the top, rear, left and right of the helmet. This type of equipment makes sure that the measuring points are identical in all tests.

This helmet is screwed on the head in 4 points. Based on the lateral and frontal X-ray photographs, the position of the helmet is defined and the distances and directions of accelerometers to the head centre of gravity can be calculated.

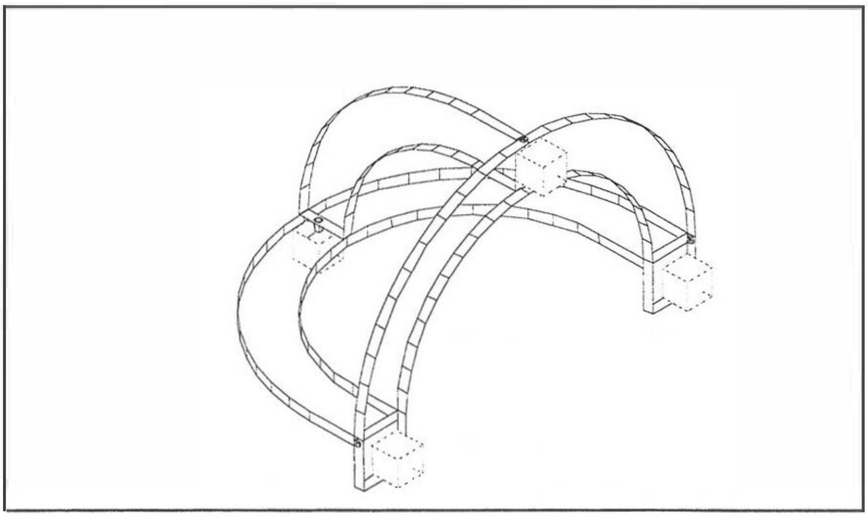

Figure 3 : The helmet with 4 sensors groups

In order to minimize the influence of the helmet mass in the results, this helmet is made of Duralinox and lightened with several holes, its stiffness remaining unchanged. The total mass (i.e. with all the sensors), is 0.3444 kg, which is less than 10% of the average head mass. However, in the calculations, the helmet mass has an effect on the observed results : then, in order to obtain accurate results, we will have to consider the group «Head + Helmet ».

The data from the 12 measurement channels constitute the basis to recalculate the resultant acceleration at the head's centre of gravity.

Kinematics - The pre-test and post-test situation of the subject was documented with colour photographs. The impact was documented with a high speed camera in lateral view with a frame rate of 1,000 pic/sec. Furthermore, a documentation of the impact phase with a digital video standard camera, with a frame rate of 25 pic/sec, was made.

Medical Investigation - The medical investigation included a face inspection about soft tissue injuries, an head autopsy with macroscopic findings of the face skull after removing the soft tissues. For tests N° 5.3/5.4 and 5.5/5.6 an additional computer tomography of the skull before the autopsy was made.

RESULTS

Mechanical response - Table 2 lists the impacted areas, the various parameters recorded during the tests and medical findings for the tests performed at INRETS and at Heidelberg. Several tests per subject were carried out. Tests from 5.1 to 5.8 and from FCA33 to FCA57 have been performed within the framework of ADRIA programme.

Head and neck responses - Table 3 lists the maximum of the force and acceleration measured on the impactor, and the head responses evaluated according to the method of Padgaonkar et al (1975).

DISCUSSION

Table 4 summarizes the characteristics of the tests carried out at Heidelberg (5.1-5.8) and at INRETS (FCA01-FCA57).

Figures 4 to 8 only present the tests carried out at INRETS and at Heidelberg which have given an injury severity of AIS >= 2. In order to compare the results, the energy was chosen on the abscissa because the impacting weight and the impactor speed are different.

Figure 4 presents the impactor force versus the energy. The impactor force, between 1500 and 3000 N, corresponds to energy between 60 and 130 J, which gave face bone fractures. The forehead fracture occurred when the impactor force reached 5000 to 7000 J. Concerning the rigid disk tests, they gave facial bone fractures, but the impactor disk had probably hit the fore head, which can explain impactor force around 4000 J ; values contained between those corresponding to direct face or forehead impacts.

Figure 5 presents the HIC value versus the energy. Although the HIC values were low (from 60 to 200), the punctual impact broke the bones. A higher energy for the padded tests gave also HIC values lower than 300. Only the rigid impact tests from Heidelberg probably hitting the skull gave HIC values from 500 to 1000. The 1000 HIC value used for the standards to evaluate the head impact severity is not well adapted when the impact is located on the face.

Figure 6 presents the maximum of the resultant acceleration at the center of gravity of the head. Although the test characteristics were different, an acceleration at around 60 g broke the bone of the face. For these cadavers, the impact on the forehead gave fractures only from 200 g.

Figure 7 presents the maximum of the resultant neck force and figure 8 presents the maximum of resultant neck moment. These values were calculated at the neck level. The average of the maximum force calculated at the head/neck junction is 2500 N and varies 1150 to 5160 N. Concerning the maximum moment calculated at the same level, the average value is 244 Nm and varies from 144 to 358 Nm. Although the energy varies from 65 to 430 J, the calculated values do not change so much. On the other hand, the impacts on the forehead gave higher values.

These results show that the HIC cannot prognosticate an injury severity of AIS >= 2 for the face bones. An impact to the face which is higher than 1600 N or a resultant acceleration at the center of gravity higher than 60 g could brake the face bones, which is independent from the energy and the kind of impact.

Table 4 test characteristics

	Heidelberg tests 5.1-5.8	INRETS tests FCA01-FCA57
impacting shape	flat disk, ϕ 15 cm rigid aluminium plate padded 40 mm foam simulating dashboard	steel cylinder ϕ 2.25 cm simulating steering wheel rim
impacting weight	23 kg	17 kg (FCA01-FCA20) 17.6 kg (FCA51-FCA57)
impact direction	45 degrees	30 degrees
total number of cadavers	4	15
number of cadavers versus sex	1 female 3 male	6 female 9 male
total number of tests	8 tests (5.1-5.8)	57 tests (FCA01-FCA57)
number of tests versus impacted areas	4 on left face 4 on right face	14 on left forehead 15 on right forehead 8 on left zygomatic 13 on right zygomatic 5 on left mandible 2 on right mandible

CONCLUSION

This study underlines the necessity of setting up limits and criteria for each part of the face and the skull. Consequently, a biofidelic improvement of dummies heads needs a differentiated treatment of each zone of the face. This study could constitute a basis to define a new injury criterion for the human face.

As part of task 2.2 of the ADRIA project, TRL and TNO have evaluated three dummy faces in terms of biofidelity and design for injury assessment. TRL have tested the AATD or THOR dummy face against three different steering wheels. TNO have carried out tests with two load sensing dummy faces, the GM face and the Volvo Load Sensing Face.

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Table 2 : Tests conditions and medical findings

Test N°	Impacted area	Impact [m/s]	velocity [km/h]	Energy [J]	Medical findings
5.1	left face, padded	3.6	13	149	no soft tissue and bony injuries AIS 0
5.2	right face rigid	3.9	14	175	open laceration AIS 1
5.3	left face, padded	5.3	19	323	fracture os maxillaris AIS 2
5.4	right face rigid	4.7	17	254	open laceration AIS1, fracture os mandibulare AIS 2
5.5	left face, padded	5	18	288	no soft tissue and bony injuries AIS 0
5.6	right face rigid	5	18	288	wide laceration AIS 1, bone fractures AIS 2
5.7	left face, padded	6.1	22	428	haemorrhage underneath the skin AIS 1, bone fractures AIS 2
5.8	right face rigid	6.1	22	428	deep skin laceration AIS 1, bone fracture AIS 3
FCA01	right zygomatic bone	1.14	4.10	11	skin laceration AIS 1
FCA02	right forehead	1.62	5.83	22	skin laceration AIS 1
FCA03	left zygomatic bone	1.78	6.41	26	skin laceration AIS 1
FCA04	left forehead	2.80	10.08	65	skin laceration AIS 1
FCA05	right zygomatic bone	1.24	4.46	13	skin laceration AIS 1
FCA06	right forehead	2.12	7.63	37	skin laceration AIS 1
FCA07	left zygomatic bone	2.15	7.74	38	zygomatic bone fracture AIS 3
FCA08	left forehead	3.14	11.30	82	frontal bone fracture AIS 1
FCA09	right zygomatic bone	1.00	3.60	8	skin laceration AIS 1
FCA10	right forehead	2.10	7.56	37	skin laceration AIS 1
FCA11	left forehead	3.04	10.94	77	skin laceration AIS 1
FCA12	left zygomatic bone	2.19	7.88	40	skin laceration AIS 1
FCA13	right zygomatic bone	1.23	4.43	13	skin laceration AIS 1
FCA14	right forehead	2.09	7.52	37	skin laceration AIS 1
FCA15	left zygomatic bone	2.09	7.52	37	skin laceration AIS 1
FCA16	left forehead	3.01	10.84	77	skin laceration AIS 1
FCA17	right zygomatic bone	1.36	4.90	16	skin laceration AIS 1
FCA18	right forehead	2.10	7.56	37	skin laceration AIS 1
FCA19	left zygomatic bone	2.11	7.60	38	skin laceration AIS 1
FCA20	left forehead	2.73	9.83	63	skin laceration AIS 1
FCA21	right zygomatic bone	1.31	4.72	15	skin laceration AIS 1
FCA22	right forehead	2.14	7.70	39	skin laceration AIS 1
FCA23	left zygomatic bone	2.07	7.45	36	skin laceration AIS 1
FCA24	left forehead	3.05	10.98	79	skin laceration AIS 1
FCA25	right zygomatic bone	1.50	5.40	19	skin laceration AIS 1
FCA26	right forehead	2.27	8.17	44	skin laceration AIS 1
FCA27	left zygomatic bone	2.33	8.39	47	zygomatic bone fracture AIS 3
FCA28	left forehead	3.16	11.38	85	frontal bone fracture AIS 1
FCA29	right zygomatic bone	1.52	5.47	20	skin laceration AIS 1
FCA30	right forehead	2.35	8.46	47	skin laceration AIS 1
FCA31	left zygomatic bone	2.58	9.29	57	skin laceration AIS 1
FCA32	left forehead	3.47	12.49	102	skin laceration AIS 1
FCA33	right zygomatic bone	3.11	11.20	82	zygomatic bone fracture AIS 3
FCA34	right forehead	2.78	10.01	66	skin laceration AIS 1
FCA35	left forehead	3.69	13.28	116	skin laceration AIS 1
FCA36	right forehead	2.79	10.04	66	skin laceration AIS 1
FCA37	right zygomatic bone	3.14	11.30	84	zygomatic bone fracture AIS 3
FCA38	left forehead	4.21	15.16	151	bone fracture AIS 1
FCA39	left mandible	1.33	4.79	15	skin laceration AIS 1
FCA40	right zygomatic bone	3.28	11.81	91	zygomatic bone fracture AIS 3
FCA41	right forehead	2.82	10.15	68	skin laceration AIS 1
FCA42	left forehead	5.76	20.74	282	frontal bone fracture AIS 3
FCA43	left mandible	1.76	6.34	26	skin laceration AIS 1
FCA44	right zygomatic bone	2.76	9.94	65	zygomatic bone fracture AIS 3
FCA45	right forehead	2.89	10.40	71	skin laceration AIS 1
FCA46	left forehead	5.81	20.92	287	skin laceration AIS 1
FCA47	left mandible	2.79	10.04	66	skin laceration AIS 1
FCA48	right zygomatic bone	3.50	12.60	104	zygomatic bone fracture AIS 3
FCA49	right forehead	3.47	12.49	102	skin laceration AIS 1
FCA50	left forehead	5.73	20.63	279	frontal bone fracture AIS 3
FCA51	right mandible	3.81	13.70	128	skin laceration AIS 1
FCA52	right forehead	4.30	15.48	163	skin laceration AIS 1
FCA53	left forehead	5.64	20.30	280	frontal bone fracture AIS 3
FCA54	left mandible	4.23	15.23	157	zygomatic bone fracture AIS 3
FCA55	right mandible	3.53	12.71	110	skin laceration AIS 1
FCA56	right forehead	5.64	20.30	280	skin laceration AIS 1
FCA57	left mandible	4.72	16.99	196	zygomatic bone fracture AIS 3

Table 6 : Impact characteristics and head responses

Test N°	Impactor force [N]	Impactor decel. [g]	Res. acc. head c.g. [g]	HIC	Res. neck force [N]	Res. neck moment [Nm]	Head rot. acc. [rad/s^2]
5.1	1580	11	57	188	1434	178	6311
5.2	3851	*	92	208	1876	204	6399
5.3	2792	11	68	178	1150	168	5345
5.4	4111	15	130	494	1970	221	7190
5.5	2724	15	75	257	951	132	4826
5.6	4577	*	184	926	4161	358	10214
5.7	1800	18	81	278	2023	144	3975
5.8	2887	20	148	539	3856	218	7733
FCA01	670	4	27	7	#	#	#
FCA02	1900	10	85	89			
FCA03	910	6	37	21			
FCA04	4410	22	170	536			
FCA05	750	5	30	11			
FCA06	2280	18	104	211	#	#	#
FCA07	1480	9	64	69			
FCA08	3580	28	166	490			
FCA09	750	6	25	9			
FCA10	2920	18	125	174	#	#	#
FCA11	4320	27	172	391			
FCA12	1690	11	66	58			
FCA13	1140	7	43	18			
FCA14	2770	15	93	121	#	#	#
FCA15	2010	11	72	72			
FCA16	4650	24	154	318			
FCA17	570	4	20	5			
FCA18	2720	20	99	140	#	#	#
FCA19	810	6	30	19			
FCA20	3240	20	121	259			
FCA21	950	9	32	11			
FCA22	2210	17	101	126	#	#	#
FCA23	1270	15	55	28			
FCA24	4700	24	244	788			
FCA25	730	5	37	20			
FCA26	2060	12	98	144	#	#	#
FCA27	*	*	*	*			
FCA28	4090	18	194	520			
FCA29	1070	7	31	13			
FCA30	4070	24	153	307	#	#	#
FCA31	2132	14	54	68			
FCA32	4420	29	184	443			
FCA33	1801	12	69	45	1528	196	5849
FCA34	2576	16	100	122	1934	200	6531
FCA35	6031	37	188	502	3096	271	8106
FCA36	3944	30	148	283	3681	337	9759
FCA37	2428	15	111	131	3005	315	8780
FCA38	4503	31	172	489	4089	499	16769
FCA39	661	4	22	6	1025	64	1389
FCA40	1596	9	81	79	2398	264	7227
FCA41	3352	20	89	181	2602	182	5243
FCA42	5149	28	201	548	4827	340	8439
FCA43	832	5	30	6	803	150	4709
FCA44	1984	12	87	94	2415	258	6340
FCA45	3317	27	143	256	3580	332	7330
FCA46	7866	67	361	1914	11290	762	17795
FCA47	1961	11	76	137	2826	302	8479
FCA48	2656	15	112	174	2281	305	7772
FCA49	5210	31	213	724	4091	311	11877
FCA50	6293	38	245	1048	5470	412	11799
FCA51	*	*	*	*	*	*	*
FCA52	6281	34	266	1300	3914	400	11029
FCA53	6950	48	365	2747	9936	663	14619
FCA54	2091	18	110	213	3222	222	10957
FCA55	1576	17	67	68	1246	168	8257
FCA56	7870	59	337	1589	6881	582	16461
FCA57	1466	15	61	58	2369	253	7176

* no signal #, not calculated

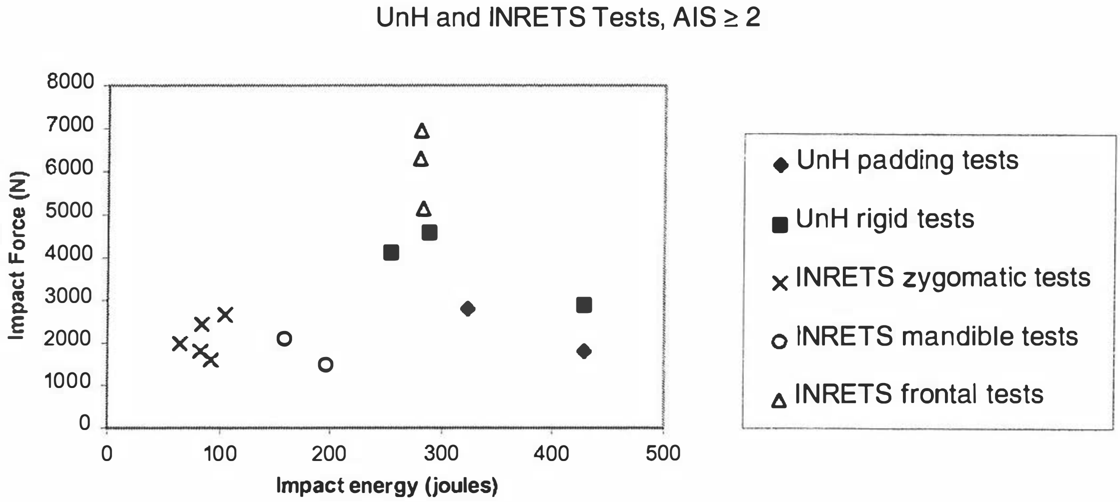

Figure 4 : Impact force versus Impact energy. Only tests with AIS ≥ 2

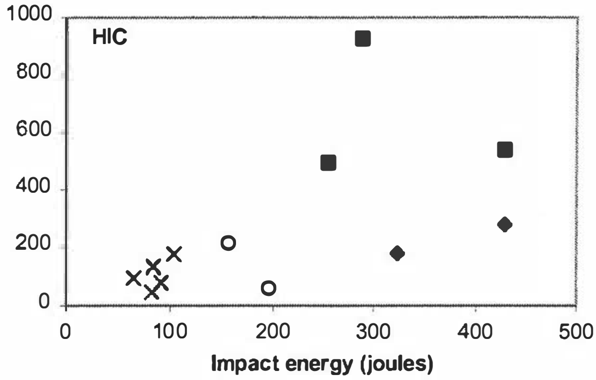

Figure 5 : HIC versus Impact energy

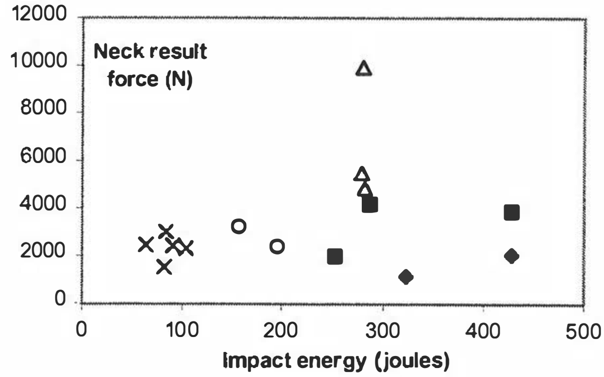

Figure 7 : Max neck result force versus Impact energy

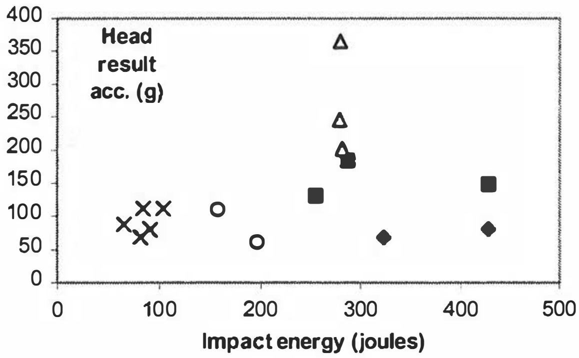

Figure 6 : Max head result acceleration versus Impact energy

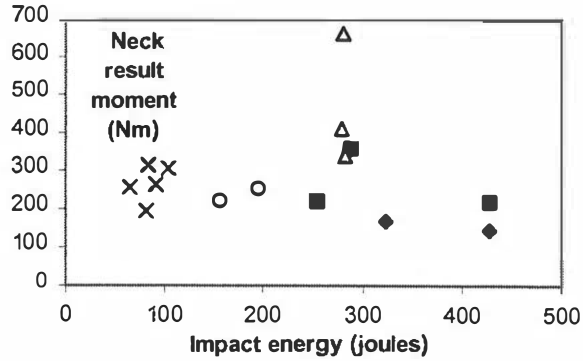

Figure 8 : Max neck result moment versus Impact energy