UPPER EXTREMITY INTERACTION WITH SIDE IMPACT AIRBAG

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ABSTRACT

Side airbag deployment tests have been conducted on the Eurosid-1, with a Hybrid-III arm, and on cadavers. The goal was to generate biomechanical data on the upper extremity during static deployment.

The belted subject, was tested on the driver side, forearm on the window sill, and on the passenger side, forearm on the armrest. Angular velocities and accelerations, and dummy internal loads were measured.

Forces measured on the dummy arm and shoulder were lower than the loads required for fracture. In one case a hand injury was observed. The dummy upper extremity and the cadaver upper extremity kinematics were widely different.

CHEST AND HEAD INJURIES, in side impacts, are numerous and are often life threatening. According to a study performed at L.A.B. PSA Peugeot Citroën - Renault, 86% of injured occupants involved in side impact crashes received injuries to the chest or to the head. For 38% of those occupants with head or chest injuries, the injuries sustained by these regions were of AIS3+. Morris et al (1997) found that, in side impacts, chest injuries accounted for 51% of AIS5-6 injuries and for 34% of AIS3+ injuries, while head injuries accounted for 28% of AIS5-6 injuries and for 23% of AIS3+ injuries. Of 113 fatal injuries, 22% were to the head and 15% were to the chest. Injuries to those body regions are frequent in side impact and are often severe. The severity of these injuries could be reduced and most of these injuries could be avoided by the use of a side impact thorax/head airbag. A study, based on the L.A.B. accident investigation data, was conducted by Foret-Bruno, to assess the percentage of fatalities, in side impact, avoided by a side airbag. He found that 12% of killed occupants and 8% of seriously injured occupants would be avoided by a chest airbag. Hassan et al (1995) established that 88% of AIS3+ injuries and 91% of AIS4+ injuries would be covered by safety devices including airbags.

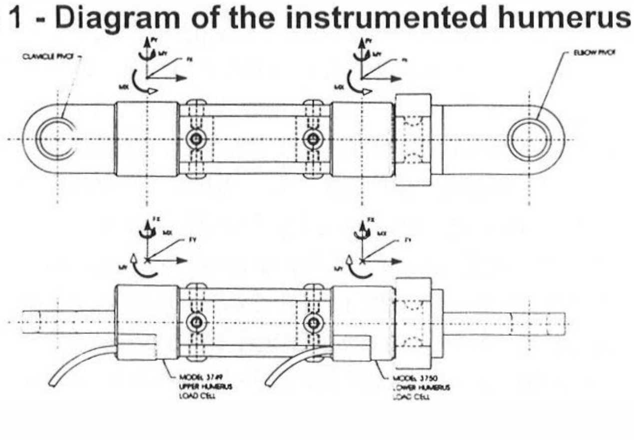
However, the side airbag could cause undesirable injuries to the upper extremity. Firstly because of the direct impact of the airbag on the arm, secondly by projecting the limb onto the vehicle interior parts. To date, the influence of the airbag on upper extremity injuries is unknown, it could mitigate these injuries, but it could also aggravate or increase them. According to Frampton et al. (1997), in side impacts, 11% of AIS2+ injuries are upper extremity injuries. 50% of these latter are shoulder injuries, 15% are humerus fractures, and 25% are forearm, wrist and hand injuries. Those results should be compared to future accident data with side airbag deployment, to define the types and the distribution of upper extremity injuries induced by the airbag. For the time being there are almost no known crash cases with side airbags, so accident data is lacking to determine the risk of upper extremity injuries due to airbag deployment. Airbag deployment tests, on a Eurosid-1 fitted with a Hybrid III arm and on cadavers, seemed to be necessary in order to understand and to assess the mechanism and risks of arm interaction with side impact airbags.

The first goal of dummy tests was to measure kinematics and forces caused by direct interaction with the airbag. Forces were measured to be compared to the injury-tolerance data, kinematics were measured to define the upper extremity motions in the vehicle interior. The second goal was to validate the methodology and the reproducibility of these tests before testing the airbag with cadavers. The first aim of the cadaver tests was to measure the arm and forearm kinematics, to determine forearm motion relative to the arm, arm motion relative to the shoulder, and upper extremity displacement in the car interior. The second aim was to evaluate upper extremity injury risk caused by the deployment of a specific airbag. At least a comparison between the dummy upper extremity kinematics and the cadaver upper extremity kinematics was provided to validate the fitted Hybrid III arm onto the Eurosid-1 dummy.

METHODOLOGY

TEST CONFIGURATIONS - The dummy tests were conducted with the Eurosid-1 with 2 different arms fitted via a purpose built ball and socket shoulder joint, and Hybrid III forearm and hand. The first arm was the DENTON 50th percentile instrumented humerus and the second one was the TAD-50th percentile dummy arm developed by NHTSA which is identical to the Hybrid III 50th percentile arm except for a slight difference in the dimensions of the shoulder joint. A diagram of the instrumented humerus is shown in Figure 1.

Figure 1 - Diagram of the instrumented humerus



The cadaver tests were conducted with 2 subjects provided by the Institute of Anatomy of the Faculté des Saints Pères, University of Paris V. The first cadaver was a female of 79 years, 160cm, 56kg, and the second cadaver was a female of 70 years, 165cm, 61kg.

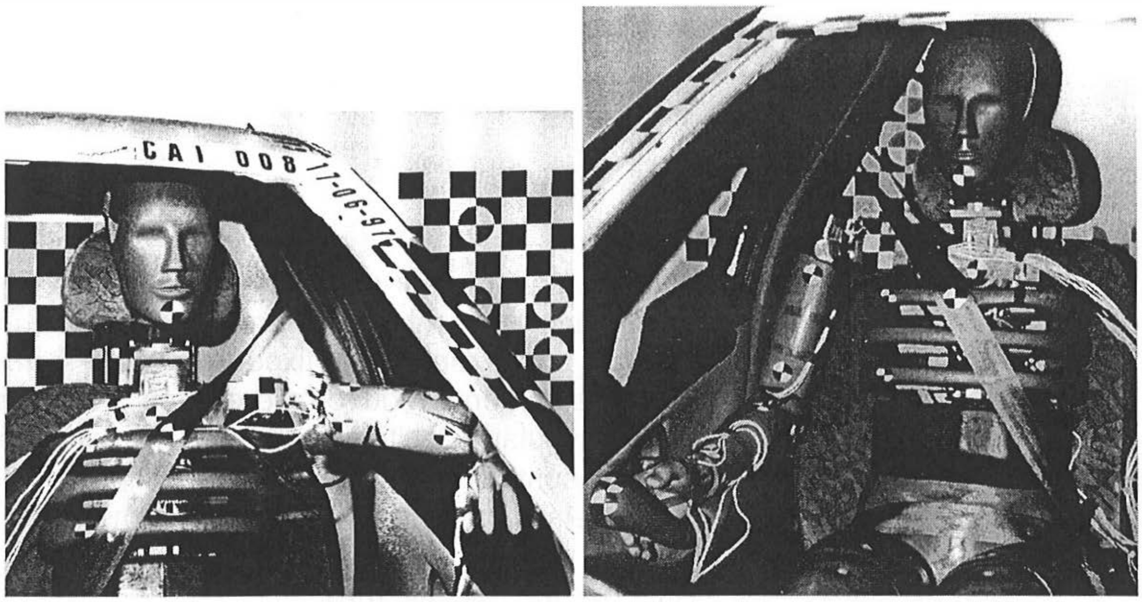
The tests were performed in a body shell of a mid-size french car cut in half behind the B-pillars, with a side thorax/head airbag mounted in the seat-back, with seat belts, door interior trim panels and window glazing. Each subject was belted and was positioned centrally on the seat, on both driver and passenger side. On the driver side the left forearm was placed on the window sill with opened window, and on the passenger side the right forearm was positioned on the armrest with hand on a hand hold. The positions, forearm on the armrest and forearm on the window sill, are described by the ISO/SC10/WG3 Test Procedure. The tests performed are summarized in Table 1, and the driver and the passenger configurations are shown in Figure 2.

Table 1 - Test matrix

	Eurosid + instrumented humerus	Eurosid + TAD arm	Cadaver 1	Cadaver 2
Driver side	●	●	●	●
Passenger side	●	●	●	●

Figure 2 - Subject positioned on the driver and passenger configurations

Driver **Passenger**

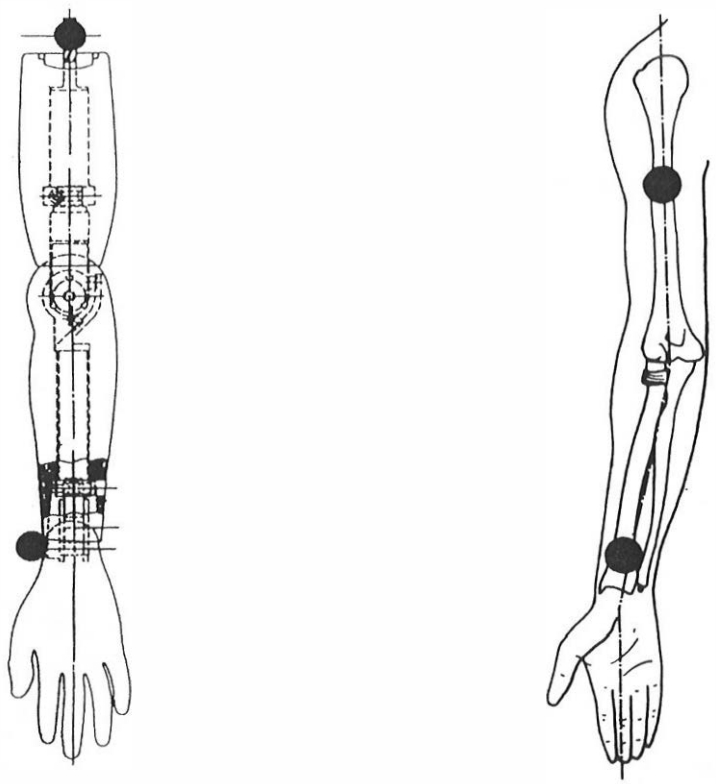


The coordinate system was defined, for the dummy, according to the SAE Recommended Practice J211 for a standing dummy with its arms at the sides. For the cadaver, the coordinate system was the same except that the palms of the hands were facing forward. The x axis was positive forward for the dummy and for the cadaver, the y axis was positive to the right for the dummy and to the left for the cadaver, the z axis was positive downwards along the dummy arm and upwards along the cadaver arm.

INSTRUMENTATION - The sensors were not located at the same points on the dummy and cadaver upper extremities (Figure 3).

Figure 3 - Sensor locations on the dummy and the cadaver upper extremities

Dummy's upper extremity **Cadaver's upper extremity**



In order to compare dummy and cadaver upper extremity accelerations, and to calculate velocities and displacements, the arm and forearm accelerations had to be calculated at the same points and in a fixed reference frame. Therefore the arm and forearm measurements required were three axis linear accelerations Ax, Ay, Az and three angular velocities ωx, ωy, ωz. The sensors were three uniaxial accelerometers mounted to a triaxial magnetohydrodynamic (MHD) angular rate sensor. The acceleration on a point P of the arm or of the forearm was calculated as

$$\vec{A_P} = \vec{A_M} + \frac{d\vec{\omega}}{dt} \wedge \vec{MP} + \vec{\omega} \wedge (\vec{\omega} \wedge \vec{MP})$$

where A_M was the measured acceleration, respectively on the arm or on the forearm. On the shoulder and on the sternum only linear accelerations were measured.

Forces were measured only on the dummy shoulder, using the Biosid shoulder triaxial load cell, and on the instrumented humerus. All measurements from the dummy and the cadavers are given in Table 2.

Table 2 - Dummy and cadaver measurements

	Eurosid + instrumented humerus	Eurosid + TAD arm	Cadaver
Sternum	- accelerations:Ax, Ay, Az	- accelerations: Ax, Ay, Az	- accelerations: Ax, Ay, Az
Shoulder	- accelerations: Ax, Ay, Az - forces: Fx, Fy, Fz	- accelerations: Ax, Ay, Az - forces: Fx, Fy, Fz	- accelerations: Ax, Ay, Az
Arm upper arm lower arm	- accelerations: Ax, Ay, Az - angular velocities: ωx, ωy, ωz - forces : Fx, Fy - moments : Mx, My - forces : Fx, Fy - moments : Mx, My	- accelerations: Ax, Ay, Az - angular velocities: ωx, ωy, ωz	- accelerations: Ax, Ay, Az - angular velocities: ωx, ωy, ωz
Forearm	- accelerations: Ax, Ay, Az	- accelerations: Ax, Ay, Az	- accelerations: Ax, Ay, Az - angular velocities: ωx, ωy, ωz
Hand	- accelerations: Ax, Ay, Az	- accelerations: Ax, Ay, Az	/

All dummy sensors were adhesive bonded. For cadavers, acromion and sternum accelerometers were fixed by screws, while MHD angular rate sensors were fixed with wire onto the radius and humerus.

RESULTS

DUMMY -

Kinematics - The accelerations measured and calculated on the upper extremity : arm, elbow and forearm, were higher for the passenger side than for the driver side. Only the shoulder acceleration was lower for the passenger side. The highest accelerations were at the elbow, 185g on the passenger side, arm on the armrest. The lowest accelerations were at the shoulder. Table 3 summarizes the maximum resultant accelerations measured for the dummy tests.

As far as arm trajectories are concerned, on both driver and passenger side the upper extremity was not flung into the vehicle interior. In the driver configuration, the dummy upper extremity exhibited a displacement of only a few centimeters. In the passenger configuration the arm was adducted by about 35° and struck the chest.

Table 3 - Dummy maximum resultant accelerations (g)

	Driver configuration		Passenger configuration	
	Instrumented humerus	TAD arm	Instrumented humerus	TAD arm
Sternum	27	12	**35**	**37**
Shoulder	**21**	**18**	9	12
Arm	21	29	**37**	**46**
Elbow	73	99	**154**	**185**
Forearm	28	21	**47**	**67**
Hand	49	12	**57**	**60**

Loads - Forces measured on the dummy arm and shoulder were lower than the loads required for fracture. The shoulder load cell allows measurement of the forces on the clavicle. Therefore shoulder measurements were compared to fracture loads defined for the clavicle by Messerer (1880) and Weber (1859). The measurement of the arm forces was compared to the humerus fracture loads evaluated by Kirkish (1996), Messerer and Weber. Forces appeared higher for the driver configuration, forearm on the window sill, than for the passenger configuration, forearm on the armrest. The dummy measured forces and the fracture loads are summarized in Table 4.

Table 4 - Dummy resultant loads and fracture loads defined by Kirkish, Messerer and Weber

	Dummy tests		Kirkish		Messerer		Weber	
	Driver	Passenger	50^{th}%ile	5^{th}%ile	Male	Female	Male	Female
Clavicle compression (kN)	0.28	0.19	/	/	1.89	1.24	/	/
Humerus bending (kN)			2.5	1.7	2.71	1.71	3.55	2.26
upper humerus	0.38	0.36						
lower humerus	0.44	0.26						
bending (Nm)			230	130	151	85	115	73
upper humerus	35	12						
lower humerus	24	21						

Airbag deployment - In both configurations the airbag deployment was correct. The force acting on the arm during the airbag deployment was calculated as

$$\vec{F}_{airbag \to arm} = m_{arm} * \vec{A}_G - (\vec{F}_U + \vec{F}_L + \vec{P})$$

where m_{arm} is the arm mass, A_G is the acceleration of the arm center of gravity, F_U is the upper humerus force, F_L is the lower humerus force and P is the arm weight. Table 5 summerizes the measured upper humerus and lower humerus forces. The evaluated force was 1.8kN, this is much lower than the forces estimated by Kallieris et al. (1997) who found forces between 4.5kN and 9kN. Nevertheless in the tests performed by Kallieris et al. the subject was placed close to the B-pillar so it was nearer the airbag, moreover Kallieris evaluated differently these forces, by multipling the arm mass by the measured resultant acceleration.

Table 5 - Measured upper and lower humerus forces (kN)

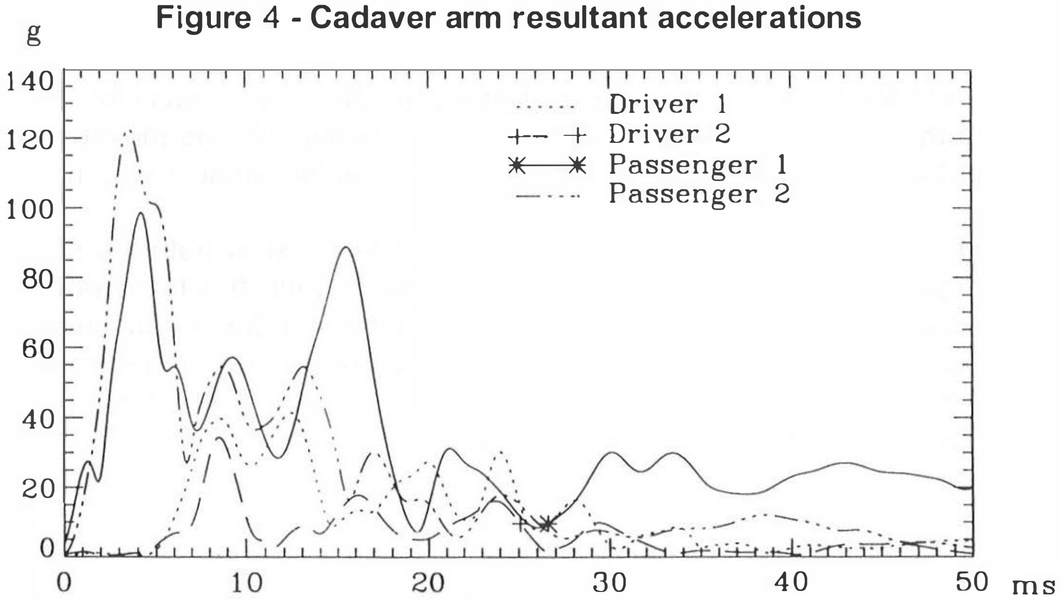
		Driver configuration	Passenger configuration
Upper humerus	F_Ux	0.38	0.29
	F_Uy	0.14	0.24
Lower humerus	F_Lx	0.39	0.18
	F_Ly	0.26	0.20

The methodology and the reproducibility of these tests could be validated by comparing the dummy responses with the instrumented upper arm to the dummy responses with the TAD arm which were similar.

CADAVER -

Kinematics - The accelerations measured and calculated on the arm were higher for the passenger configuration tests (Figure 4).

Figure 4 - Cadaver arm resultant accelerations



The highest resultant accelerations were at the elbow in the passenger configuration, and the lowest were at the sternum. Table 6 summarizes the maximum resultant accelerations measured for the cadaver tests.

Table 6 - Cadaver maximum resultant accelerations (g)

	Driver configuration		Passenger configuration	
	Cadaver 1	Cadaver 2	Cadaver 1	Cadaver 2
Sternum	10	11	7	**20**
Acromion	32	17	**57**	**83**
Humerus	42	34	**99**	**123**
Elbow	122	112	**267**	**357**
Radius	**150**	45	**97**	78

In the first driver configuration test the upper extremity was projected upwards, the forearm passed through the opened window and dropped onto the thighs. Whereas in the second driver configuration test the arm was not projected, it sustained a low displacement of about 10cm upwards and about 5cm forward. In both the passenger configuration tests the arm rotated a little relative to the shoulder, the forearm rotated a little relative to the arm, whereas the shoulder sustained a high elevation. In the first passenger test the hand slipped from the hand hold and dropped onto the thighs even though in the second test the hand stayed on the hand hold pulling it away from the door.

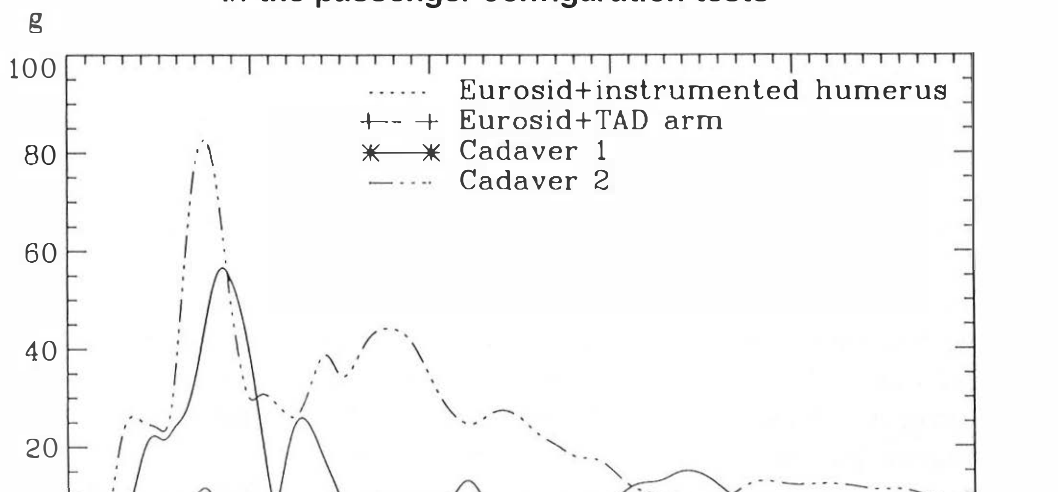
Autopsy - After each test a thorough autopsy was performed on the upper extremities, the shoulders and the chest. No shoulder, elbow, arm, or forearm injuries were observed. For cadaver 1, fractures of the 2nd, the 3rd, and the 4th right ribs were observed. These fractures certainly existed before the test and were not caused by the deployment of the airbag, that was confirmed by the review of the test films. For cadaver 2 a fracture of the trapezium of the right hand was observed. This fracture occured because the hand got jammed on the hand hold. This injury is less severe than the injuries observed by Kallieris et al. (1997) and Duma et al. (1998). Kallieris et al. found humerus fracture in one case and in an another case a rupture of the capsule of the shoulder joint, with subluxation. Duma et al. found elbow injuries, in 7 of the 12 cadaver tests. However in the tests performed by Kallieris et al. the subject was close to the B-pillar, in the tests performed by Duma et al. the occupant was moved outboard and the humerus across the airbag, in both cases the subject was nearer the airbag.

Airbag deployment - In the second driver test and in both the passenger configuration tests, the airbag deployment was correct, the head portion was not blocked and it deployed behind the arm. In the first driver configuration test the head portion of the side airbag was blocked by the arm, therefore the head portion impacted the arm during its deployment, and it slipped in front of the arm. That is probably why the arm was projected in this test.

DISCUSSION

No correlation between forces measured on the dummy and the cadaver injuries was established. Differences between the dummy and the cadaver upper extremity behaviors were identified. The analysis of the measurements and the films showed a real difference between the interaction of the airbag with the dummy arm and the interaction of the airbag with the cadaver arm. In both driver and passenger configurations shoulder accelerations and motions were higher for the cadaver than for the dummy (Figure 5). The shoulder kinematics were different for the dummy and the cadaver. This had also been observed by Kallieris et al. (1997) and Duma et al. (1998).

Figure 5 - Dummy and cadaver shoulder resultant accelerations in the passenger configuration tests



These differences could result from the purpose-built ball and socket shoulder articulation fitted to the Eurosid-1 dummy. Indeed the Eurosid-1 shoulder with or without this modification does not allow vertical translation motion, possible with the human shoulder.

These differences could also be explained by the difference of dummy and cadaver anthropometry (Table 7).

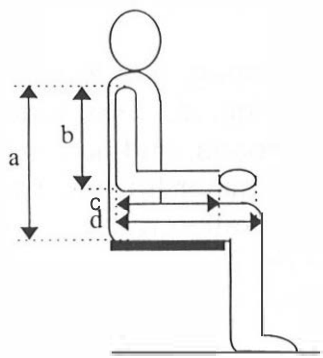
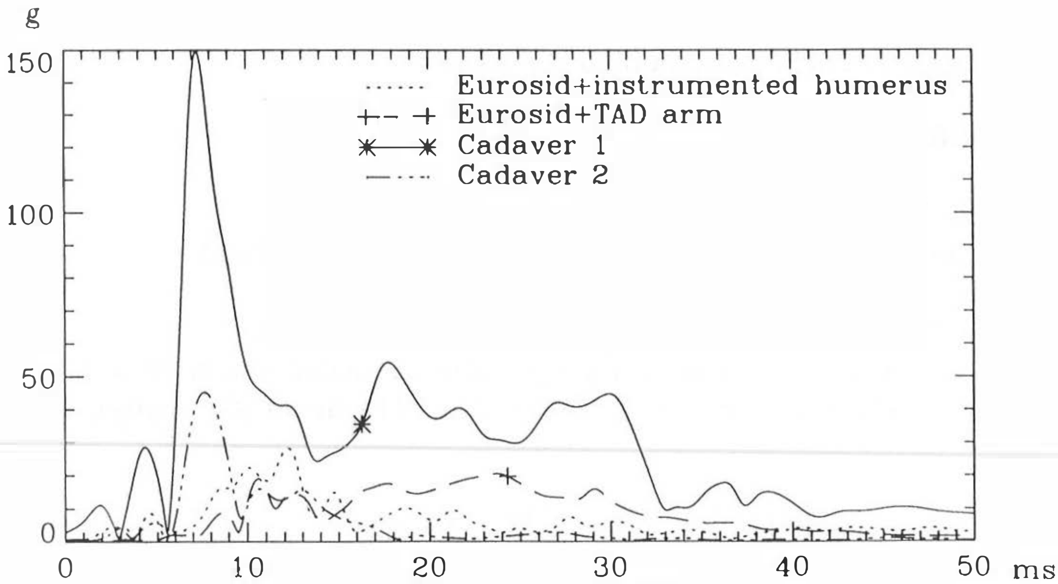


Table 7 - Cadaver anthropometry (mm)

	Cadaver 1	Cadaver 2
height	1600	1650
a=shoulder/seat plane	630	605
b=shoulder/elbow	348	345
c=elbow/wrist	250	245
d=elbow/fingers	420	430

The Eurosid-1 has the height of a 50th percentile male whereas the female statures were 1m60 and 1m65. Therefore the position of the shoulder and of the arm, relative to the airbag, was different for the dummy and for the cadaver. The directions and forces of the airbag impact on the dummy arm and on the cadaver arm were different. The female upper extremities were smaller than the Hybrid III upper extremity. That is probably why the forearm accelerations were much higher for the cadaver than for the dummy in the driver configuration tests (Figure 6).

Figure 6 - Dummy and cadaver forearm resultant accelerations in the driver configuration tests



CONCLUSIONS

The static side impact airbag deployment tests, presented in this paper, were intended primarily to verify that there were no undesirable secondary effects caused by this device while interacting with the arm. Secondly, the comparison between the human upper extremity behavior and the dummy upper extremity behavior, in these configurations, was intended to provide necessary knowledge for defining a biofidelic test device.

The results showed that the injury risk with the tested airbag, due to direct impact or to projection during static deployment is minimal. The loads measured on the Eurosid-1 were below the known fracture loads, and no major injury, in the cadaver tests, was observed. Meanwhile, one minor fracture was observed to the hand trapped in the hand hold. This configuration was chosen to be one of the worst observable cases in a 'normal position'.

Great differences were observed between the kinematics of the dummy upper extremity and those of the cadaver upper extremity. At the time being, no biofidelic test device is available. The results of this testing emphasize the need for new data, in particular for the definition of the shoulder motions of translation and of the upper extremity kinematics. Some further biomechanical tests are required to allow the definition of an optimization tool for both car manufacturers and restraint device designers.

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