HUMAN HEAD AND CERVICAL SPINE BEHAVIOUR DURING LOW-SPEED REAR-END IMPACTS: PMHS SLED TESTS WITH A RIGID SEAT

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ABSTRACT

Because of the increasing protection offered by recent cars, the neck has become a challenging question during the past decade. However, no biofidelic tool for low speed rear-end impact is available at the moment, and additional biomechanical data are still needed to refine the existing dummies or numerical models. Within the framework of the European project " Whiplash ", we carried out several tests aiming at obtaining a detailed description of the human neck behaviour in low speed rear-end impact. The emphasis was put on the kinematics acquisition at different vertebral levels.

Key words: NECK, BIOMECHANICS, REAR IMPACTS, CADAVERS

INTRODUCTION

Neck injuries in car collisions constitute a serious problem with tremendous implications for individuals as well as for society as a whole. These injuries particularly occur in rear-end impacts (Temming, 1998). Not only are these low severity injuries difficult to assess on a medical basis, but they also are difficult to predict with currently available simulation tools. This is mainly a consequence of the limited knowledge on neck injury mechanisms. In order to refine or develop new dummies or numerical models some kinematics and kinetics data are needed concerning head-neck complex behaviour.

Many rear-end impact experiments with volunteers (Mertz 1967, McConnell 1993, Matsushita 1994, Geigl 1998, Szabo 1996, Siegmund 1997, Ono 1997, Davidson 1998 and Van den Kroonenberg 1997) and with PMHS (Mertz 1967, Kallieris 1996 and Geigl 1994) were performed, mainly over the last few years. However, due to the use of standard car seats, often with headrests (McConnell 1993, Matsuchita 1994, Geigl 1994, Szabo 1996, Siegmund 1997, Davidsson 1998 and Van den Kroonenberg 1997) their boundary conditions are difficult to reproduce. Furthermore, little data is available concerning the T1 vertebra kinematics (Siegmund 1997, Ono 1997, Davidsson 1998 and Van den Kroonenberg 1997), the cervical spine behaviour (Ono 1997) and the neck loading with headrest (Van den Kroonenberg 1997).

In order to complete these data we carried out rear impact sled tests with Post Mortem Human Subjects (PMHS). The objective of this study was to investigate head and neck responses in low speed rear-end impact conditions. We focussed on the head kinematics, the T1 vertebra motions as well as the cervical spine and head-neck joint kinematics.

MATERIALS AND METHOD

TEST SET-UP. Tests with unembalmed cadavers, coming from the service for the gift of the body — René Descartes Medical University — were carried out by CEESAR with the agreement of its ethical committee. A rigid seat with a removable padded headrest was mounted on a mini-sled (Figure 1). The sled was propelled by an air piston up to the chosen velocity and consequently the head was submitted to a backward acceleration with regard to the sled (which is similar to the behaviour of a car occupant who experiences a rear-end collision). The sled deceleration was tuned in order to be less severe than the acceleration. The subject was seated with the shoulders and the pelvis against the seatback, and the thorax, the pelvis and the lower limbs were secured with straps. The seat height and the headrest position were adjustable with shims. The head was maintained in position prior to testing thanks to an electromagnet, the Frankfort plane being maintained horizontal (Figure 1). The electromagnet was released at the moment of impact.

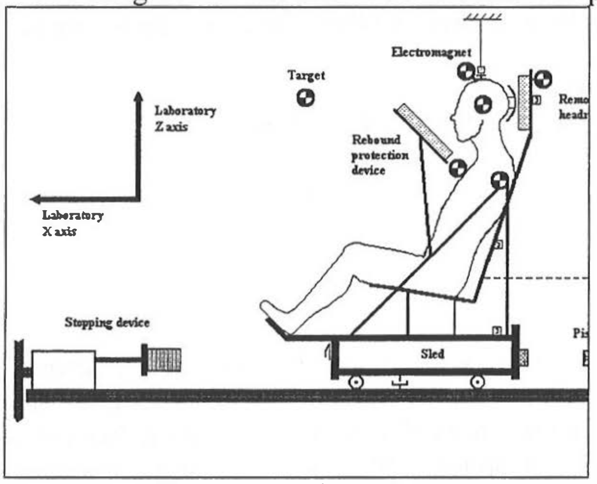

Figure 1: testing set-up

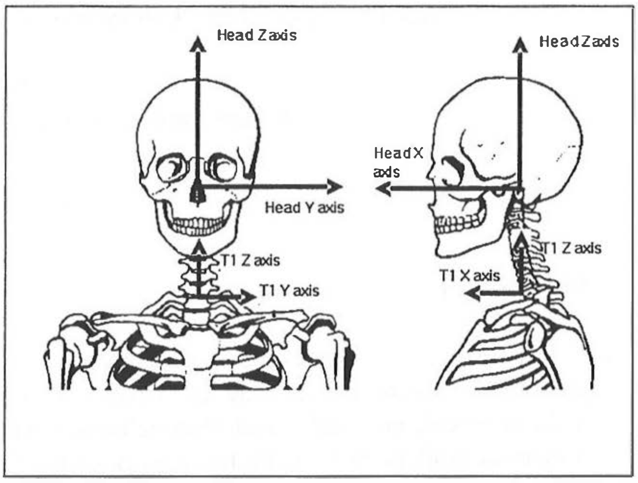

Fig. 2: reference axis systems for the head and T1

Three different configurations were tested with each subject and for the last subject, two other configurations were added in order to study the influence of a padded surface between the seatback and the subject's back. The test matrix was established as described in Table 1.

	W/o head-rest	With head-rest	
	3 m/s	3 m/s	4.5 m/s
Without padding on seat back	6 tests, 2 per cadaver	6 tests, 2 per cadaver	3 tests, 1 per cadaver
With padding on seat back	2 tests, 1 cadaver	2 tests, 1 cadaver	

Table 1: test matrix

Each configuration at 3 m/s was tested at least twice in order to evaluate its repeatability. The chosen loading conditions were kept under the injury threshold and enabled to carry out several tests with the same PMHS. The indicators for continuing the tests were the neck mobility and the condition of the fixation of the measuring devices.

COORDINATE SYSTEM. The laboratory reference system was determined by the horizontal X-axis, which was parallel to the sled displacement, and positive in the direction of the piston outstroke (Figure 1). The Y-axis was horizontal and perpendicular to X. The Z-axis was vertical, positive upwards. The head axis frame was based on the Frankfort plane, passing through the centre of the auditory meatuses and the infraorbital notches (Figure 2). The origin of the reference system of the T1 vertebra was located at the anterior-superior edge of the vertebral body (Figure 2). One of the hypotheses made during those tests was that the movements were located in the sagittal plane, and the measurments were consequently recorded in this plane. However, for the sake of verification, a linear accelerometer was mounted on the head in the Y direction.

INSTRUMENTATION. The following tables (Tables 2 and 3) summarise the instrumentation used in the tests. The different sensors used were: ± 50 g piezoresistive uniaxial accelerometers (EGAS

Entran); ± 100 rad/s magnetohydrodynamic angular velocity transducer (ARS ATA); ± 700 N and ± 20 N.m three axes - 2 forces and 1 moment - transducer (T2FM Mistral).

Measure	Directions in laboratory coordinate systems	Sensor
Piston acceleration	X	1 uniaxial accelerometer
Sled acceleration	X	1 uniaxial accelerometer
Seat back acceleration	X and Z	2 uniaxial accelerometers
Head rest acceleration	X and Z	2 uniaxial accelerometers
Sled displacement and velocity	X	1 cable transducer
Impact	Contact	

Table 2: testing set-up instrumentation

Measure	Directions in head coordinate system	Sensor
Head linear acceleration	directions X, Y et Z	3 uniaxial accelerometers
Head angular velocity	direction Y	1 angular velocity transducer
Skull cap forces and moment	directions X, Z et Y	1 three axes force transducer

Table 3: head instrumentation

The head angular velocity along the Y-axis was measured at the level of the left temple (Figure 3). The sensor support was screwed on the skull. The same method was used to adjust the parallelism between the support Y-axis and the head Y-axis. The mass of the support with its sensor was 130 g. The forces along the X and Z-axes and the moment along the Y axis between the head and the headrest were measured thanks to a skullcap transducer (Figure 4). The sensor support was screwed onto the skull. The way the fixation was achieved didn't enable to have the sensor axes parallel to the head axes. The angle was measured and accounted for in the computation of the resultant forces. The total mass of the device equipped with the transducers was 190 g.

The C2, C5 and T1 vertebrae were instrumented. A mounting box (to protect and correctly position the sensors) was screwed onto the anterior part of each vertebral body. This instrumentation installation required a fine dissection of the anterior part of the neck, without any muscular injury. X-ray photographs enabled to verify the positioning of the sensors. This verification allowed the precise definition of the co-ordinate systems. One mounting box equipped with its sensors weighed 50 g.

A 16 mm film 1000 f/s was used. Two targets were attached to the subject's head (figure 1). The first was associated with the angular velocity sensor, on the left temple. The second was glued onto the supporting device of the electromagnet. This device was screwed at the top of the skull, aligned with the theoretical centre of gravity axis of the head. Its mass was 35 g. Another target was secured on the manubrium sterni through a screwed supporting device.

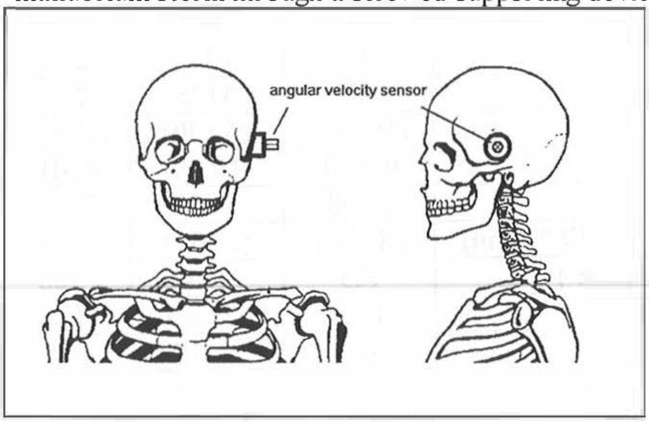

Fig. 3: head angular velocity sensor.

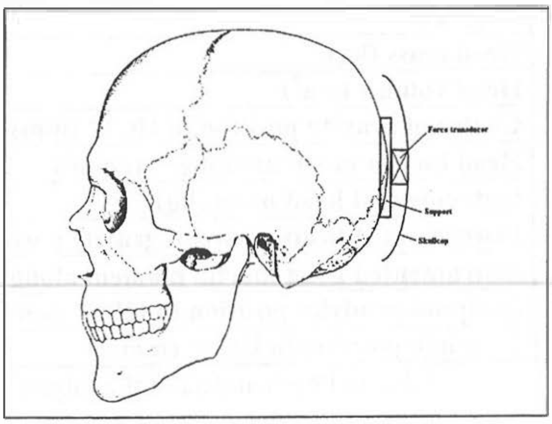

Figure 4: Force measurement between the head and the headrest.

Measure	Direction in vertebral coordinate systems	Sensor
T1 linear accelerations	directions X and Z	2 uniaxial accelerometers
T1 angular velocity	direction Y	1 angular velocity sensor
C5 linear accelerations	directions X and Z	2 uniaxial accelerometers
C5 angular velocity	direction Y	1 angular velocity sensor
C2 linear accelerations	directions X and Z	2 uniaxial accelerometers
C2 angular velocity	direction Y	1 angular velocity sensor

Table 4: Vertebrae instrumentation

POST-EXPERIMENTAL DISSECTION AND MEASURMENT. A post-experimental dissection was achieved for the verification of the absence of any injury. In order to allow head mass and inertia measurements to be made, the head was separated from the body at the level of the occipital condyles. The head was weighed according to Archimede's principle. The head centre of gravity position was assessed from profile photographs of the head suspended by a thread. The inertia moment along the head Y axis was assessed with an oscillating plate.

RESULTS

Tested specimens: Nineteen tests with three cadavers were performed. The subjects are referenced as follows: MS506 (5 tests), MS507 (5 tests) and MS511 (9 tests). Table 5 summarises the anthropometric data for the three tested PMHS.

PMHS N°	506	507	511
Age	77	85	78
Sex	Male	Male	Male
Mass (kg)	49	51	48
Height (cm)	162	165.5	164.5
Seated height (cm)	84	86	84
Head circumference (cm)	52	56.5	53.5
Head length (cm) (anterior-posterior)	18.5	19.5	17.5
Head-Headrest distance (cm)	3.5	6.0	6.0 (7.0*)

Table 5: General anthropometric data - *: test with seatback padding added

Table 6 gives the position of the head centre of gravity, the mass, the volume and the inertia moment along Y-axis of the head. The position of the centre of gravity of the instrumented head is also given, together with the position of the occipital condyles, and of the T1 vertebra which is derived from the X-rays. The mass and inertia of the instrumented head were computed using the known masses and positions of the transducers.

PMHS N°	506	507	511
Head mass (kg)	2.840	3.575	2.770
Head volume (cm^3)	2834	3175	2528
Centre of gravity position in HCS* (mm)	(15 ; 33)	(6 ; 30)	(10 ; 38)
Head inertia moment along Y (kg.m^2)	0.0121	0.0182	0.0103
Instrumented head mass (kg)	3.300	4.035	3.230
Instrumented head centre of gravity position in HCS* (mm)	(8 ; 35)	(2 ; 31)	(6 ; 39)
Instrumented head inertia moment along Y (kg.cm^2)	125	184	106
Occipital condyles position in HCS* (mm)	(-11 ; -26)	(-11 ; -26)	(-11 ; -26)
T1 origin position in HCS* (mm)	(-26;-145)	(-19;-180)	(-35;-142)

Table 6: Physical data of the subject's head and neck. - *HCS: Head Coordinate System.

Tests without headrest at 3 m/s: The T1 vertebra exhibited large displacements during these tests, with a maximum Z displacement ranging from 33.5 to 51.5 mm and a maximum extension angle comprised between 13.5 and 20.5 degrees (figures 5 and 6).

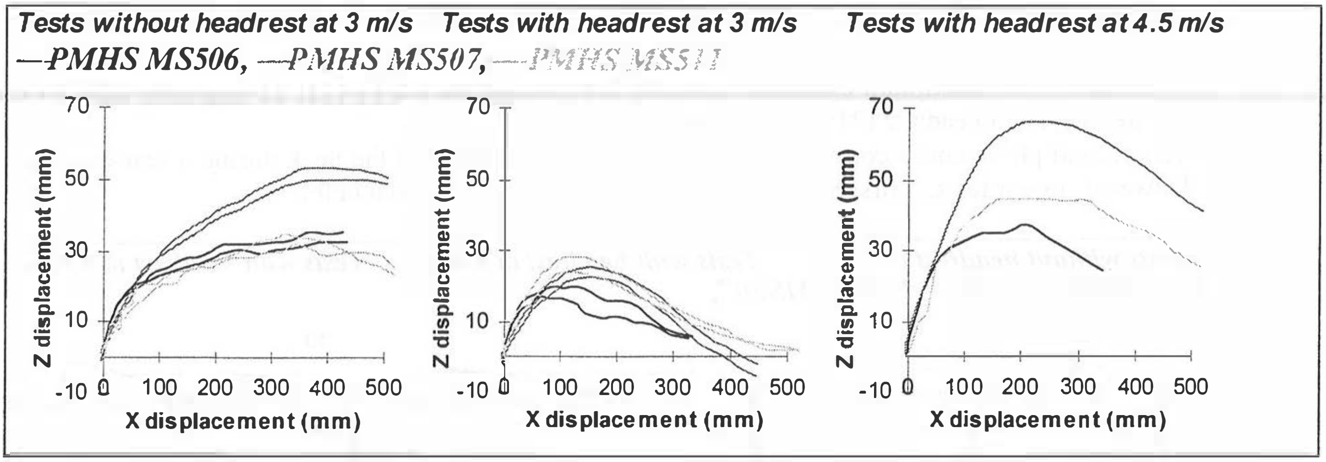

Figure 5: T1 vertebra origin displacements, in laboratory coordinate system.

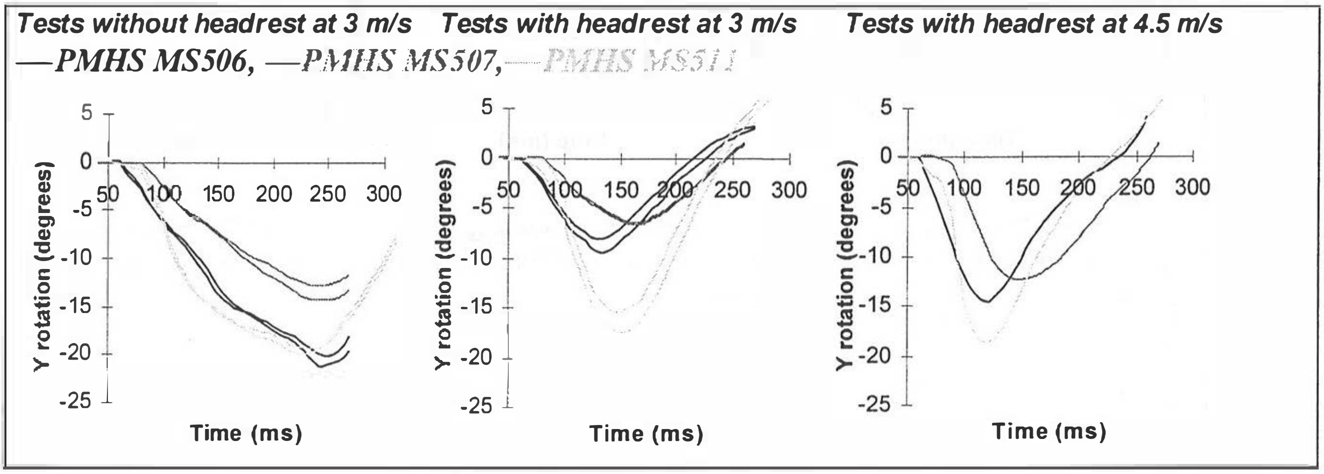

Figure 6: T1 vertebra rotations, in laboratory coordinate system.

The head displacements with regard to T1 along the X direction were equivalent for all the tested subjects and ranged from 155 to 177 mm. The Z head displacements versus T1 were subject-dependent. For two subjects, a descending movement (-Z displacement) was observed during the impact, while for one of the subjects, an initial rising phase (+Z displacement) was observed. The maximum descending values ranged from 70.5 to 102.5 mm. The head rotation versus T1 was also subject-dependent (figure 7). Two subjects exhibited an initial flexion, followed by an extension ranging from 40 to 58.5 degrees. For the third subject, only an extension was observed, with a maximum value of 48 degrees.

The linear and angular accelerations of the head were similar for the three subjects. The X acceleration was always positive and ranged from 47.5 to 54 m/s^2. The Z acceleration was first positive (25; 32.5 m/s^2) then negative (-30.5; -39 m/s^2). The angular acceleration was negative (-200; -300 rad/s^2), then positive (441; 581 rad/s^2). The forces and moment at the level of the occipital condyles , expressed in the anatomical head reference frame (see figure 2) can be characterised by three main phases:

- Phase 1: the neck is submitted to a compression force (111; 172 N) and a shear anterior-posterior force, with a flexion moment (2.5; 3 N.m)
- Phase 2: a traction force (neck tensile force) appears and the moment is not far from zero.
- Phase 3: all the maximum values are reached: traction force (78; 99 N), anterior-posterior shear force (126; 156 N), and extension moment (-13.5; -14.5 N.m).

These three phases were also observed for the cervical spine movements, concerning the relative rotations of T1, C5, C2 and head (figure 8):

- Phase 1: the head remains almost horizontal. A slight flexion is observed between C5 and T1, a slight extension between C2 and C5 and a slight flexion between C2 and head.

- Phase 2: extension of the lower cervical spine, relative flexion of the head versus C2 (9; 15.5 degrees). The head extension begins in the laboratory co-ordinate system.
- Phase 3: the maximum extension rotations are reached for C5/T1 (11; 15 degrees), C2/C5 (9; 20 degrees) and head/C2 (21; 22.5 degrees).

The second phase could correspond to the well-known S shape of the neck during a rear-end impact. However, in our tests, a first S shape, of a lower magnitude, appeared before.

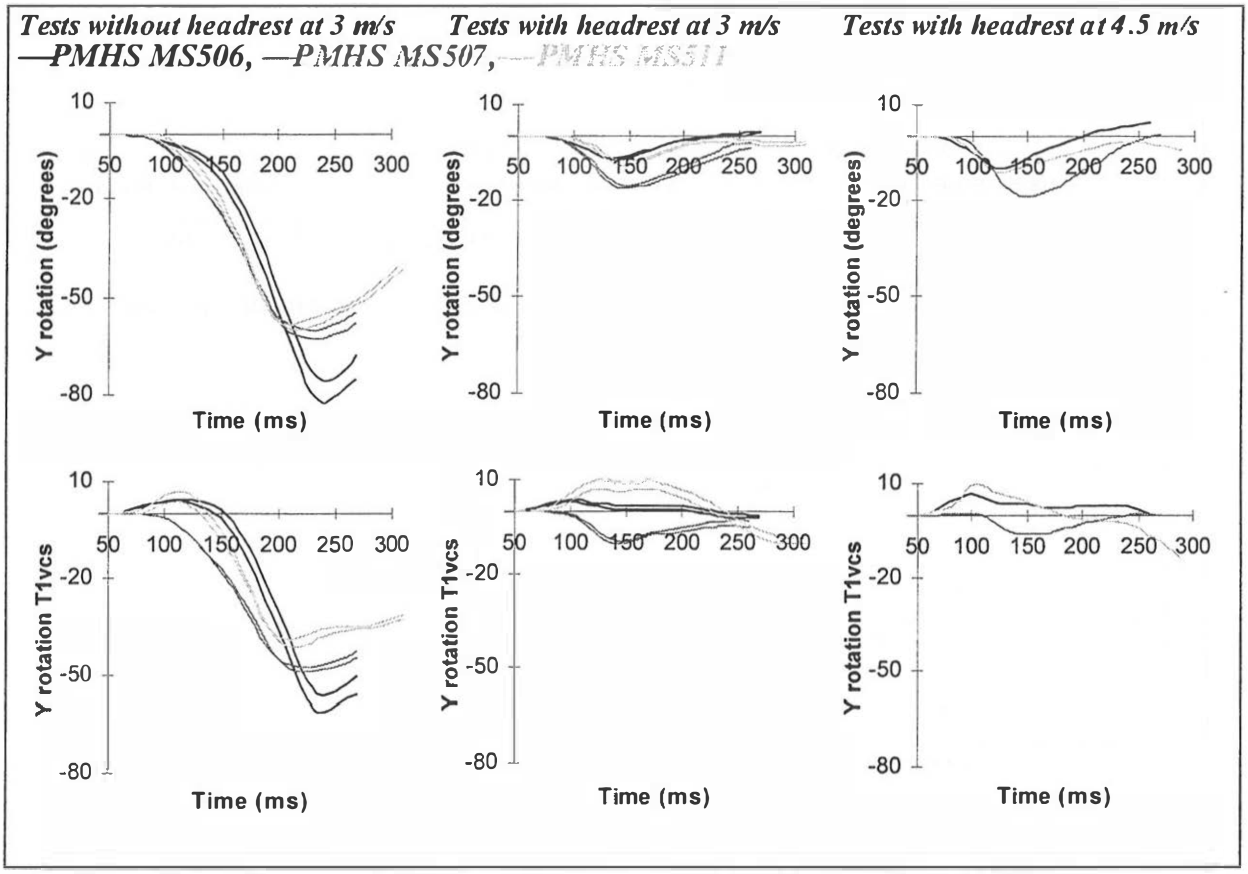

Figure 7: head rotations in the laboratory and in the T1 vertebra coordinate systems (T1vcs).

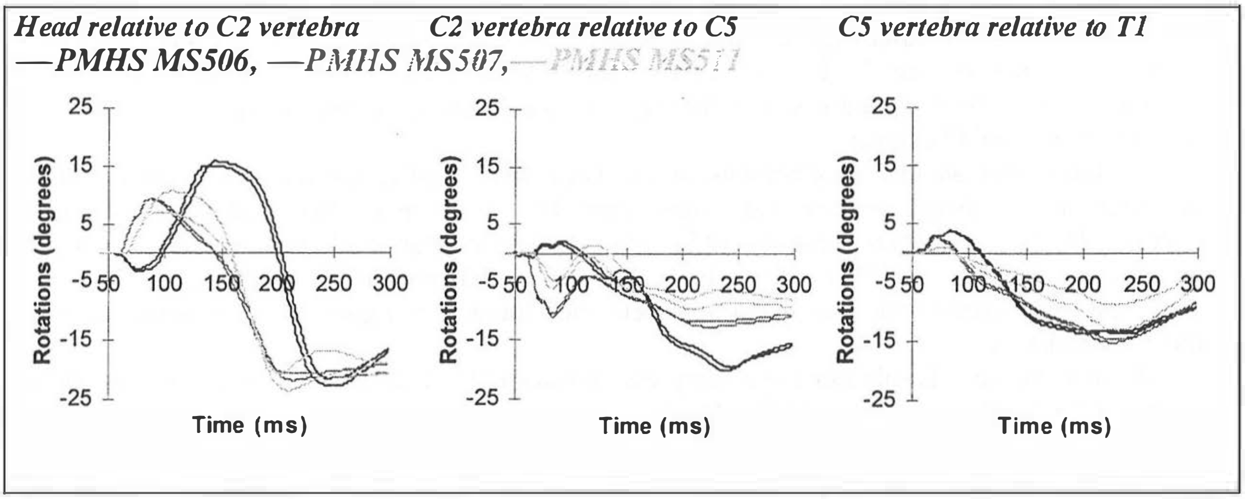

Figure 8: relative rotations of the different vertebrae and of the head. Tests without headrest at 3 m/s.

Tests with headrest at 3 m/s: Concerning T1 and head movements, the same phenomena were observed as for the tests without headrest, but with lower amplitudes of the movements (figures 5 and 6). The inter-individual dispersions were also observed with the same trends with and without headrest. The maximum accelerations of the head were of the same order of magnitude. The X acceleration was always positive, ranging from 55.5 to 67 m/s2. The Z acceleration was positive (18.5; 32 m/s2) then negative (-18; -27.5 m/s2). The Y angular acceleration was first negative (-127; -183 rad /s2), then positive (234; 338 rad /s2). The curve shapes are different from the moment of contact with the headrest. The forces exerted by the headrest on the head for the X component, ranged between 137 and 144 N, were higher than for the Z component between 46 and 67 N. The headrest affected the forces and moment exerted by the head on the neck at the level of the occipital condyles:

- X force is positive (53; 83 N), and the maximum is reached during the contact between the head and the headrest. The maximum however is lower than the maximum reached during phase 3 of the tests without headrest.
- The Z force is negative (-93.5; -154 N) and equivalent with and without headrest. After the contact, the Z force becomes positive (traction 45; 101 N), and is reached earlier than for the tests without headrest but with a same order of magnitude.
- The Y moment is always positive (2.5; 7 N.m) and is higher than for the tests without headrest.

Tests with headrest at 4.5 m/s: The increase of velocity leads to similarly shaped curves with increasing values. The most sensitive parameters can be summarised as follows:

Parameter	Multiplying factor
Z movement of T1 (37; 66 mm)	2.2
Head X acceleration (89; 130 m/s^2)	1.9
Head Z positive acceleration (-45; -61 m/s^2)	2.4
Head Z negative acceleration (49; 52 m/s^2)	2.0
Angular head acceleration (-218; -312 rad/s^2)	1.9
X force between head and headrest (251; 423 N)	2.3
Z force between head and neck (163; 248 N)	2.9

Table 7: relationships between the parameters depending upon the testing speed

Tests with seatback padding: The padding used for our tests had only a minor influence on the results. Only the traction force of the head on the neck increased significantly (factor 1.9 with regard to the test without padding). The rotations of the vertebrae were slightly affected by the padding: it led to a more pronounced S shape of the neck.

DISCUSSION:

METHOD:

Testing set-up: We chose to use a simplified rigid seat for the sake of reproducibility. We however verified that a padded seat-back did not drastically modify the head-neck complex behaviour. In the same manner, a rigid vertical shell covered by padding constituted the headrest. It was positioned in order to fit the recommendations described in the literature (height above the top of the head (Cullen 1996), low horizontal distance (around 50 mm) (Olsson 1990)). The velocity chosen (10.8 km/h) corresponded to the most frequent ΔV observed during rear-end accidents (Hell 1998). Moreover, Mertz (1967) and Kallieris (1996) already achieved tests without headrest for higher velocities (16 and 25 km/h). The tests with headrest were usually carried out with volunteers and thus with an impact velocity lower than 10 km/h. Our tests with headrest at 16.2 km/h were significantly more severe and allowed the influence of velocity to be quantified.

Instrumentation: Head and thorax kinematics have been frequently studied with accelerometric measurments and high-speed films. However cervical vertebra kinematics and force between head and headrest are rarely available in the published experimental results. Ono (1997) studied vertebra kinematics with cine-radiography. This non-invasive method does not affect motions and can be performed with volunteers. Acquisition speed is, though, 90 frame per second, which is low for one crash motion (approximately 25 frames). Moreover, limited field vision doesn't allow the visualisation of the entire cervical spine (range of C2 to C6). Finally, image analysis is difficult. Vertebra kinematics was obtained by high-speed video by Geigl (1994) and Yoganandan (1998). The former presented cadaver tests with target on a beam screwed in vertebral bodies and passing through lateral soft tissues (including sternocleidomastoid muscle). These beams could modify tissues and thus neck behaviour. Moreover, their considerable length doesn't allow precise vertebra kinematics to be obtained. Yoganandan presented cervical spine tests with soft tissues partially removed in order to visualise targets directly fixed on vertebral bodies. The influence of this loss of tissues on the neck behaviour wasn't quantified.

The method used during our tests allowed cervical vertebra kinematics acquisition using accelerometers. The instrumentation mounting boxes rigidly screwed onto vertebral bodies and their limited dimensions didn't modify anterior soft tissue behaviour. Moreover, all neck tissues were preserved. Acquisition frequency was 1000 Hertz. Only three vertebrae could be instrumented but the whole cervical spine was studied (head, C2, C5 and T1 vertebra). Each instrumentation mounting box with its sensors weighed 50 g, which was about 25 % of the mass of one vertebral level (vertebra plus its layer of soft tissues). However, the cervical spine wasn't deformed by these added masses and the kinetic loading was mainly due to the head mass. Linear accelerations and angular velocity were directly obtained. Vertebra rotation was easily obtained by integration. However, because the vertebrae initial positions were not accurately measured (no X-rays taken in the seated position), and because of the necessity of a double integration, the vertebrae displacements were not easy to obtain. The process we used for the T1 displacements was the double integration of the accelerometric signal, combined with the assessment of the initial position thanks to the thorax target.

Van den Kroonenberg (1997) gave an estimation of the headrest forces by strain gauges mounted on one of the headrest support rods. A static calibration of these strain gauges was achieved by applying load to the centre of the headrest cushion perpendicular to the support rods. However, the direction and location on the head of the headrest force were not known during impact and assumed parallel to the X anatomical axis for calculation, the point of application being assessed from the film analysis.

In our study, direct measurments of the efforts and moment applied by the headrest on one well-located point of the head were achieved. Thus precise forces and moment acting at the occipital condyle joint could be computed.

PMHS subjects: This study was achieved with three subjects, which is comparable to the samples used in other PMHS studies (2 subjects for Mertz (1967) or Kallieris (1996) and 6 for Geigl (1994)). All subjects were elderly males (between 77 and 85 years). It is known, according to Watier's study (1997) that the neck static mobility decreases with age (about 40% less for septuagenarians than for 20-39 year old people). However, this decrease is to some extent compensated by the absence of muscle tone (Wismans 1997 and Bendjellal 1987). All subjects were very thin, with low limb muscular masses. Their weights were around the 5th percentile of the French driver population (Rebiffé 1981). The subjects were also quite small, their heights ranging from the 15th to the 30th percentile adult male. However, their seated heights were closer to the average, ranging from the 25th to the 40th percentile. Table 8 gives the comparison between the PMHS head inertial properties as measured in-house and as calculated according to Clauser (1969) and MacConville (1980). Head mass and moment of inertia for PMHS subjects were low compared with mean head values, even with instrumentation mass added during tests (see Table 6). Estimations calculated with regressions overestimated all characteristics in by 14 % to 60 %.

Comparison with other studies without headrest: table 9 presents peak values obtained during cadaver or volunteer rear-end impact tests without headrest, according to different authors (Ono 1997, Mertz 1967 and Kallieris 1996) and to the present study. The test set-up is similar for all these studies, but impact velocities ranged from 8 to 26 km/h, our study at 10.8 km/h being in the lower part of this range. All results obtained during our tests agreed with the other results and are in general included between Ono's results at 8 km/h with volunteers and Mertz's (1967) results at 16 km/h with volunteer and cadavers. The T1 ramping-up and extension observed in our study is of the same order of magnitude as those observed by Ono (1997). Linear accelerations of the head center of gravity obtained during our tests are logically lower than those obtained by Mertz (1967). Head center of gravity displacements with respect to T1 vertebra are of the same order of magnitude in the X-axis and significantly lower in the Z-axis than in Kallieris's (1996) tests.

	Subject MS506		Subject MS507		Subject MS511		Head bibliographic mean values
	Measure	Estimation	Measure	Estimation	Measure	Estimation	
Head mass (kg) (1)	2.840	3.954	3.575	4.452	2.770	4.095	4.730 (Clauser 1969), 4.059 (Becker 1972), 4.376 (Walker 1973), 3.980 (Reynolds 1975), 4.305 (Beir 1980)
Head volume (cm^3) (2)	2834	3394	3175	4245	2528	3840	4418 (Clauser 1969), 3947 (Walker 1973), 4369 (McConville 1980)
Head moment of inertia Iyy ($kg.cm^2$) (2)	121	138	182	219	103	165	237 (Becker 1972), 223 (Walker 1973), 164 (Reynolds 1975), 223 (Beier 1980), 232 (McConville 1980)

Table 8: Subject and average head inertial properties.
Comparison between measurment and literature estimations:
(1) Clauser's regression (1969) and (2) MacConville's regression (1980).

	Ono (1996)		Mertz (1967)			Kallieris (1996)	This study
Subjects (1)	3 V M	3 V M	1 V M	2 C M	2 C M	2 C M	3 C M
Number of tests	3	3	1	2	2	2	6
DV (km/h)	8	8	16	16	24	26	10.8
Test type	Sled	Sled	Sled	Sled	Sled	Sled	Sled
Seat	Rigid	Standard	Rigid	Rigid	Rigid	Rigid	Rigid
Tl acceleration (m/s^2)	55	50	40	50	70	70	50 to 75
Tl ramping (mm)	32	25					34 to 52
Tl rotation (degrees)	20	20					14 to 21
Head CG X-axis acceleration (m/s^2)			40	70 to 100	110 to 120	100 to 115	48 to 54
Head CG Z-axis acceleration (m/s^2)			50	60 to 80	140 to 150	125 to 150	31 to 39
Head CG resultant acceleration (m/s^2)	40	60	64	92 to 128	178 to 192	160 to 180	
Head CG X-axis displacement (mm)						145 to 237	155 to 177
Head CG Z-axis displacement (mm)						133 to 168	71 to 103
Head angular acceleration (rad/s^2)					500 to 750	720 to 760	441 to 581
Head rotation (degrees)	80	70	37	61 to 64	84 to 86	74 to 100	59 to 79
OC shear force (N)	150 to 240	40 to 250	218	245 to 400	271 to 441	345 to 360	126 to 156
OC traction force (N)	100 to 200	250 to 300	125	187 to 312	419 to 504	446 to 473	78 to 99
OC compression force (N)	150 to 400	50 to 350					111 to 172
OC extension moment (N.m)	8	6	17	20 to 37	34 to 45	36 to 39	14 to 15

Table 9: Peak values obtained during rear-end tests without headrest.
(1) Number of subjects, V volunteers or C cadavers, M male or F female.

Head angular accelerations obtained during our tests are, logically, lower than those obtained for 25 km/h velocity. Peak head extensions were of the same order of magnitude in our tests as in tests at 8 and 16 km/h. Forces at the level of occipital condyles reported by Ono have a great range. Those obtained during our tests are in the lower area of these and are, logically, lower than Mertz's results. Peak extension moments obtained during our study are between those obtained during Ono's (1997) and Mertz's (1967) studies. These peak values show that our results agreed with literature ones. Moreover we observed, as Ono did, a head flexion relative to the thorax at the beginning of the impact. Ono also observed an initial relative flexion of the lower cervical spine, which was obtained between C5 and T1 vertebrae in the first phase of our tests. Yoganandan (1998) already described the important initial flexion of the upper cervical spine obtained during our tests on the isolated head and neck system.

	McConnell (1993)	Matsu-shita (1994)	Szabo (1996)	Siegmund (1997)	Davids-son (1998)	Van den Kroonen-berg (1997)	This study
Subjects (1)	8 V M	16 V M 3 V F	7 V M 3 V F	20 V M 19 V F	4 V M	7 V M 1 V F	3 C M
Number of tests	24	19	17	39	5	10	6
DV (km/h)	2.5 to 11	2.5 to 5.0	8 to 10	8	7	6.5 to 9.5	10.8
Test type	Vehicle	Sled	Vehicle	Vehicle	Sled	Sled	Sled
Seat	Standard	Standard	Standard	Standard	Prototype	Standard	Rigid
T1 acceleration (m/s²)		16 to 29	45 to 74	27 to 59	35 to 50	48 to 72	50
T1 ramping (mm)					27 to 35	24 to 43	19 to 26
T1 rotation (degrees)				14 to 20	12 to 16	12 to 20	7 to 16
Head CG X-axis acceleration)m/s²)	60 to 100		61 to 148	70 to 100	40 to 50		56 to 67
Head CG Z-axis acceleration (m/s²)	50 to 70		32 to 162	10 to 30	20 to 35		19 to 32
Head CG resultant acceleration (m/s²)		27 to 63	66 to 172	67 to 120		64 to 124	
Head CG X-axis displacement (mm)					60 to 100	40 to 50	40 to 73
Head CG Z-axis displacement (mm)					5 to 30		8 to 19
Head angular acceleration (rad/s²)	600 to 1500			450 to 1260		400 to 1000	234 to 338
Head rotation (deg.)	30 to 60			9 to 33	20 to 25	7 to 30	7 to 17
Headrest X-axis force (N)						280 to 470	137 to 144
OC shear force (N)						30 to 190	53 to 83
OC traction force (N)						40 to 50	45 to 101
OC compression force (N)						180 to 310	94 to 154
OC flexion moment (N.m)						13 to 40	3 to 7

Table 10: Peak values obtained during rear-end tests with headrest.

(1) Number of subjects, V volunteers or C cadavers, M male or F female

Comparison with other studies with headrest: table 10 presents peak values obtained during cadaver or volunteer rear-end impact tests with headrest, according to different authors (McConnell 1993, Matsushita 1994, Szabo 1996, Siegmund 1997, Davidson 1998, Van den Kroonenberg, 1997) and to our study. All these studies, except ours, were carried out with volunteers seated in a deformable seat (standard or prototype). Velocities are in general close to 10 km/h (between 7 to 9 km/h). Thus, our test conditions were not similar to those of the other studies. However, kinematics results obtained during our tests are in agreement with the other results. T1 vertebra ramping and extension were observed during recent studies with similar magnitude as in ours. Head centre of gravity linear accelerations have great peak value dispersions within each study and between different studies. The values we obtained corresponded to the low end of the values coming from the other studies. Head centre of gravity displacements relative to T1 are of the same order of magnitude as those reported by other authors.

Peak head angular accelerations, obtained during our tests, were lower than those from the other tests. These peak values were observed during head to headrest contact and the difference between our seat and headrest conception and standard seats could explain that phenomenon. Peak head extension obtained during our tests and the other tests were of the same order of magnitude. However our values are relatively low due to initial head to headrest distance which is quite low in our tests. Only Van den Kroonenberg's study (1997) gives an estimation of forces and moment during the impact. For these tests, force between the head and the headrest is calculated from headrest support rods deformations. In order to compute forces and moment at level of occipital the condyles, the author assumed that this force acted only in X-axis of the head.

Forces between head and headrest obtained during our tests were much lower than those calculated by Van den Kroonenberg. Moreover, we observed that during our tests the force in the Z-axis represents 33 to 46 % of the one in the X-axis. Comparison of values obtained at the level of the occipital condyles was thus delicate. Indeed, although the shearing forces are of the same order of magnitude for both studies, the axial forces were very different. The differences were not restricted to peak values. Whereas Van den Kroonenberg's study shows first a traction then a compression during head to headrest contact, our result show a compression followed by a traction. A relative flexion moment appeared in both studies with lower values in ours. Kinematics results obtained during our tests are in agreement with the literature even with different testing conditions. The initial flexion phase of the head relative to T1, observed by Davidson (1998) and Van den Kroonenberg (1997) was also observed in our study.

CONCLUSION

Nineteen tests with 3 PMHS were achieved corresponding to common automotive rear-end impacts. Three test conditions were studied: velocity of 3 m/s without headrest, velocity of 3 m/s with headrest and velocity of 4.5 m/s with headrest. For all these tests, the curves describing displacements, rotations, linear and angular accelerations of the head and T1 vertebra, plus the forces and moments acting at the level of occipital condyles joint were given. Moreover, for the tests without headrest the kinematic behaviour of the cervical spine was presented.

Even though the number of subjects is too low to conclude definitively, we can observe tendencies. For all the tests a significant ramping-up motion as well as extension movement of T1 was observed. During tests without headrest, loading as well as neck kinematics were characterised by three main phases. Within the first phase, the neck was subjected to a compression force with anterior-posterior shear and a little flexion moment. The lower cervical spine (between T1 and C5 vertebrae) was slightly flexed, the mid cervical spine (between C5 and C2) was extended and the upper cervical spine (between C2 and the head) was flexed. The head stayed almost horizontal. A traction force on the neck accompanied by a shear force characterised the second phase. The moment at the occipital condyles joint was almost zero. The whole inferior cervical spine (between T1 and C2) was extended and the upper cervical spine remained flexed. The head began its extension relative to the laboratory. During the third phase, traction force, shear force and an extension moment reached their peak values. The whole cervical spine was extended.

During our tests with headrest, the head contact occurred towards the end of the first phase or at the beginning of the second phase. The forces and moment at the occipital condyles differed from this time. Shear force was always anterior-posterior but its peak value was lower than without headrest. Compression force (before contact) but also traction force were of the same order of magnitude as without headrest. The moment obtained with a headrest was a flexion moment during the whole impact.

The increase of velocity, during tests with headrest, led to an increased magnitude. The most sensitive result was the neck tensile force that was tripled when the velocity increases from 3 to 4.5 m/s.

These results agreed with available literature results, but most of all they complete these data. Indeed, they describe neck behaviour for some different test conditions and velocities. Moreover, the vertebra kinematics and headrest to head is new data not found in previous studies. This force measurement allows precise study of the headrest influence on neck loading. These complete and detailed results as the well-controlled boundary conditions allow the elaboration of a new reference database for determining rear-end biofidelity of crash dummies or mathematical models.

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