

Considerations for a Neck Injury Criterion

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ABSTRACT

A kinematic analysis of the head-neck unit has been conducted in 37 simulated traffic accidents in order to investigate correlations between neck response and injuries. Belted fresh human cadavers in the age range 18 to 74 years have been used as front and rear-seat passengers.

The analysed data included 23 frontal collisions, impact velocity 30 km/h, 50 km/h and 60 km/h, barrier impact and 14 90°-car to car lateral collisions with near-side passengers (6 cases) as well as far-side rear-seat passengers with an in-board upper anchoring point for the shoulder belt (8 cases).

The head bending angle depended on the type of the collision. At the frontal collision, the mean head bending maxima amounted 79°, the evaluated mean angular velocity maxima and angular acceleration maxima corresponded to 41 rad/s and 2208 rad/s², the mean maximum velocity in trajectory of the head was 10 m/s, the mean maximum acceleration along the path amounted 23 g.

With the same collision velocity of 50 km/h in the 90°-car to car lateral collision higher mean values of head bending angle maxima were observed in the near-side front passengers (62°) than in the far-side rear-seat passengers (57°). The evaluated angular velocity maxima and angular acceleration maxima amounted in the mean for the near-side passengers 43 rad/s and 2887 rad/s², the mean maximum velocity in trajectory of the head amounted 8 m/s, the mean maximum acceleration along the path was 33 g; for the far-side passengers the mean angular velocity maxima of 26 rad/s were evaluated, for the angular acceleration it was 1345 rad/s², for the head velocity in trajectory 10 m/s and for the acceleration along the path 18 g.

Injuries of AIS 1 (hemorrhage = strain) already occurred at an angular acceleration of 560 rad/s² or a head acceleration of 13 g along the path, whereas the cervical spine may remain uninjured at an angular acceleration of still 2470 rad/s² or head acceleration of 23 g along the path. On the other hand, an AIS 3 was observed at an angular acceleration of 1320 rad/s² or a head acceleration of 22 g

along the path, and an AIS 4 of 4910 rad/s² or a head acceleration of 39 g along the path.

INTRODUCTION

Whiplash or cervical spine injuries are associated with dynamic forces transmitted, direct or indirect to the human head-neck unit and were known at first in rear-end car impacts. Especially, in the time when the seats were not yet equipped with head rests. In rear-end impacts a hyper-extension of the head-neck occurs which results in injuries of the cervical spine. The hyper-extension may also be caused by the head of the not belted front occupant striking against the windshield, the windshield header or the dashboard during the frontal collision. With the increasing use of the 3-point belt it was noticed that the restraint effect of the torso leads to a hyperflexion of the head-neck and also to whiplash injuries. In the side impacts being topical at present also whiplash injuries of the cervical spine were observed as result of the lateral hyperflexion.

Since more than 20 years investigations concerning the kinematic and response of the inhomogeneous structure of the cervical spine were conducted by means of volunteers and cadaver tests, by isolated head-neck models and finally, by mathematical simulations (2-7, 15-21)*. Compared to the head, thorax, abdomen and pelvis, the neck has a negligible injury frequency (3,11,13).

However, whiplash injuries of AIS 1 and AIS 2 may also lead to complaints of a long duration according to the age of the occupant; this is important to the forensic point of view (Insurance cases) whereby the occurrence of the cervical spine trauma has to be brought in connection with the accident severity. Present published data predominantly concern head-neck responses in volunteer tests and lesser in cadaver tests. One way to express the response of the cervical spine is to determine the bending

* Numbers in parentheses designate references of end of paper

angle, the angular velocity and the angular acceleration from the high speed movies.

The aim of the paper is to investigate correlations between neck responses and injuries of the cervical spine in a greater number of cadaver tests, also if the tolerance level is exceeded.

MATERIAL

The investigated collective included 43 simulated collisions using post mortem human subjects. 28 of them were frontal collisions with a Δv of 30, 50 and 60 km/h, the occupants were protected either by a 3-point standard belt (9), a double shoulder-lap and inverted V-pelvic belt (21), and a combination of 3-point belt with pretensioner. The frontal collision tests with some important data are listed in Table 1.

The second collective included 15 tests in which the occupant protected by a 3-point belt, was used as far-side or near-side occupant and loaded through lateral collision in full scale or sled tests. In the sled tests, the $\Delta v = 30$ km/h and 35 km/h; in the full scale tests it was $\Delta v = 25$ km/h (car to car side collisions) (12, 13). Some important data of this collective are given in Table 2. The age range of both collectives amounted 18 to 74 years.

METHOD

The kinematic behaviour of the neck was investigated in detail during the impact. The high speed film (frame rate 1000 p/s) of the camera was mounted onto the side of the sled for frontal collisions and onto the front of the struck vehicle for side collisions, both used and projected to a HP Graphics Tablet. According to the collision type, x- and z-coordinates for the front collisions, and y- and z-coordinates for the side collisions, the fixed points of sled and vehicle and the optical targets at the body and head of the test subject (Fig. 1, 2) were scanned over the time, digitized and stored in a HP PC. The flexion angle of the head-neck for frontal collisions is formed out of two optical target pairs (head, lower cervical spine-pelvis) which each define a straight line (Fig. 1).

In the same manner is the lateral bending angle of the head-neck formed out in the frontal collisions by using two optical target pairs (head, thorax) which each define a straight line (Fig. 2).

By the application of computer programs, especially developed for this evaluation, the flexion and the lateral bending angle of the head-neck, the angular velocity of the head and the angular acceleration of the head are evaluated over the time and illustrated with a printer. A further program was developed in order to evaluate the velocity in trajectory of the head by using the geometric addition of the derivation of the displacement in x- and z- or y- and z-direction $V(t) = \sqrt{\dot{x}^2 + \dot{z}^2}$, $V(t) = \sqrt{\dot{y}^2 + \dot{z}^2}$ and the head acceleration along the path by using the derivation of the velocity in trajectory (Fig. 3 and 4). In order to establish reasonable derivations of the present time-histories, it was necessary to smooth the curves. A program was developed

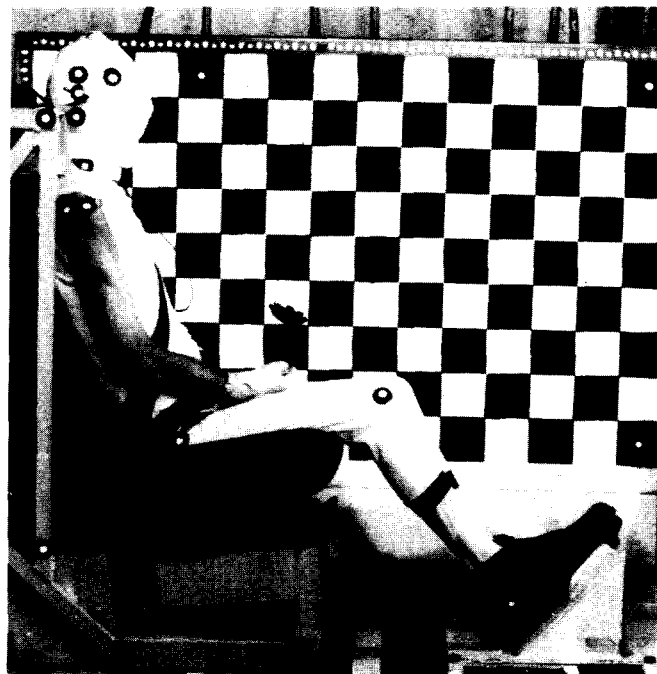


Fig. 1: Location of the optical targets at the body of the subject by the frontal collision tests



Fig. 2: Location of the optical targets at the body of the subject by the side collision tests

which at first decomposes the data by means of Fourier transformation and then rejects all values above a certain filter frequency. The curve transformed back is therefore automatically smoothed. The filter frequency of 20 Hz reproduced the original run of the angle-time-history in the best manner possible.

RUN NO	IMP.VEL. KM/H	MEAN SLED DEC. (g)	SEX	AGE (Y)	HEAD CIRC. (cm)	NECK CIRC. (cm)	RESTR. SYSTEM
7702	30.2	14.10	M	18	53	36.0	3PT/STAN
7704	29.9	13.30	M	46	54	35.0	3PT/STAN
7801	30.6	11.90	W	34	53	33.0	3PT/STAN
7804	30.8	12.20	M	29	53	38.0	3PT/STAN
7805	30.6	12.40	M	49	56	37.5	3PT/STAN
7905	50.0	15.20	M	39	58	45.0	3PT/STAN
7906	49.0	14.50	M	21	52	34.5	3PT/STAN
7907	49.8	15.30	M	50	53	43.0	3PT/STAN
7908	49.5	14.30	M	19	57	38.0	3PT/STAN
7909	49.8	14.65	W	25	51	39.0	3PT/STAN
7911	50.0	14.46	M	25	55	40.5	3PT/STAN
7912	48.0	11.50	M	51	58	32.0	3PT/STAN
7915	50.0	15.30	M	22	57	33.0	3PT/STAN
7916	50.0	15.70	W	39	54	34.0	3PT/STAN
7917	50.0	16.40	M	18	55	37.0	3PT/STAN
7918	50.0	14.57	M	23	52	34.0	3PT/STAN
7919	50.0	15.61	M	51	55	39.0	3PT/STAN
8001	49.5	16.10	M	38	56	39.0	3PT/STAN
8002	49.9	16.10	W	32	52	31.0	3PT/STAN
8006	50.9	14.70	W	34	54	32.0	3PT/STAN
8618	59.2	11.00	W	61	55	36.0	6POINTB.
8622	59.2	11.30	M	37	57	38.0	6POINTB.
8706	59.4	15.20	M	50	59	43.0	6POINTB.
8709	60.5	15.50	M	27	58	39.0	6POINTB.
8710	60.8	15.50	W	43	53	33.0	6POINTB.
8808	50.4	10.40	M	29	57	38.0	3PT/STAN
8915	49.9	17.00	M	63	59	47.0	3PT+PREL
9013	47.5	16.00	M	34	58	38.0	3PT/STAN

Table 1: Impact severity, some anthropometric data and restraint system of the frontal collision tests
(3PT/STAN = 3-point standard belt; 6POINTB. = double shoulder lap and inverted V-pelvic belt;
3PT+PREL = 3-point belt with pretensioner)

RUN NO	IMP.VEL. KM/H	IMPACT POSITION	SEX	AGE (Y)	HEAD CIRC. (cm)	NECK CIRC. (cm)	RESTR. SYSTEM
8825	49.0	FAR S.	M	59	57	46.0	3PT/STAN
8831	48.9	FAR S.	W	74	55	32.0	3PT/STAN
8832	29.7	FAR S.	W	46	56	35.0	3PT/STAN
8834	49.5	FAR S.	W	54	56	39.0	3PT/STAN
8904	50.0	FAR S.	M	55	57	42.0	3PT/STAN
8905	49.1	FAR S.	W	24	54	35.0	3PT/STAN
8907	30.0	FAR S.	W	60	56	38.0	3PT/STAN
8931	35.8	FAR S.	M	46	54	41.0	3PT/STAN
8535	50.0	NEAR S.	M	43	55	39.0	3PT/STAN
8537	50.6	NEAR S.	M	22	58	41.0	3PT/STAN
8538	50.2	NEAR S.	M	44	55	38.0	3PT/STAN
8546	50.4	NEAR S.	M	46	56	43.0	3PT/STAN
8547	50.0	NEAR S.	M	39	57	36.5	3PT/STAN
8607	50.0	NEAR S.	M	41	58	43.0	3PT/STAN
8935	50.0	NEAR S.	M	32	56	38.0	3PT/STAN

Table 2: Impact severity, some anthropometric data and restraint system of the side collision tests

Investigation and Injury Severity of the Vertebral Column

The spinal column with the base of the skull was extracted from the body and, in a frozen condition sawed to pieces in the mean x-z plain and the two x-z parallel planes through the lateral joints and was then evaluated (14).

The injury severity of the observed lesions was scaled in accordance with AIS 1990 (1). Injuries not included in the AIS were scaled according to our long-standing biomechanical experience.

RESULTS

Kinematic - Frontal collision

In the test subjects using either a three-point belt or a double shoulder-lap belt or an inverted V-pelvic belt occurred during the crash phase an antelexion of the head after a translatory displacement. The translatory movement lasted about 30 to 70 ms beyond the crash, dependant of the restraint system and the impact velocity, then followed a combined movement in x- and z-direction. During this phase an elongation of the whole cervical spine was observed, simultaneous with a compression load at the front and an additional extension of the cervical spine's rear side.

Fig. 3 shows an example of three characteristic positions of a subject's head, restrained by a three-point belt, in regard to the location of the target for the evaluation of the velocity in trajectory and the acceleration along the path of the head. According to the asymmetric protection of the thorax through the shoulder belt in the 3-point belt protected cases a rotation of the torso and the neck-head system around the shoulder belt resulted in a time of 70-100 ms after the crash. Cases with evident rotation are not included in the evaluations.

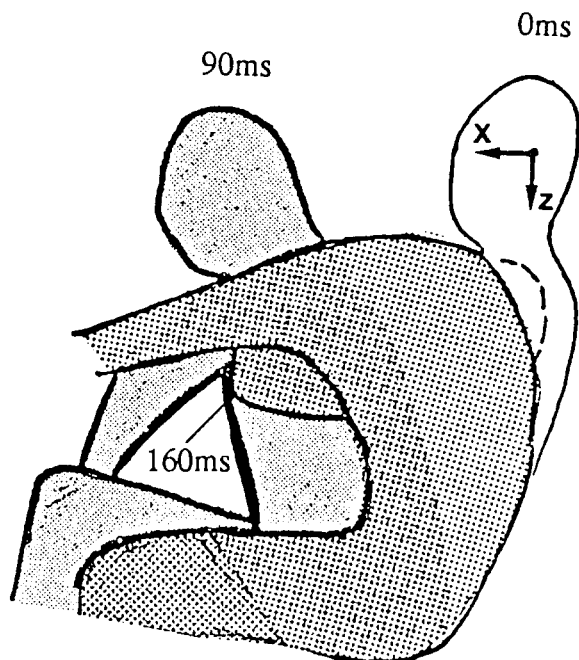


Fig. 3: Head anatomical origin with characteristic positions of head's kinematic in x-z-plane, frontal collision (Run No. 7801)

Kinematic - Side collision

In the near-side passenger protected by a conventional 3-point belt as well as in the far-side passenger protected by a 3-point belt including an inboard upper anchoring point for the shoulder, a lateral displacement of the head with respect to the torso was observed. For the near-side passengers this time amounted about 20 to 30 ms, for the far-side passengers 80 to 100 ms. After the lateral displacement of the head, a lateral bending towards the impact side occurred. During this loading phase a tension load occurred on the far-side and a compression on the near-side of the cervical spine.

Fig. 4 shows an example of three characteristic positions of the head of a far-side subject protected by a three-point belt; here too, the point is illustrated which was used to evaluate the velocity in trajectory and the acceleration, along the path. Also in the side collisions a rotation of the head around the z-axis was observed, however, cases with an evident rotation were not evaluated and are therefore not included in the results.

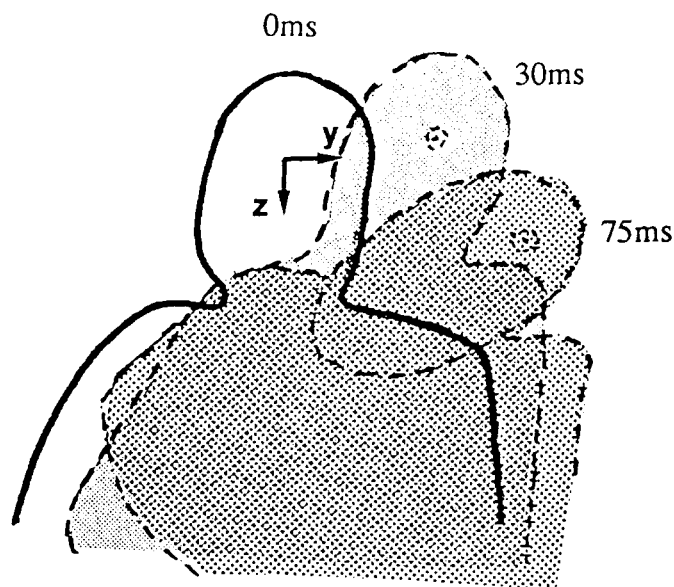


Fig. 4: Head anatomical origin with characteristic positions of head's kinematic in the y-z-plane, side impact (Run No. 8904)

Data Evaluation

All data evaluated by the high speed film analysis were illustrated versus the time. Fig. 5 shows the example of one test. In this test the male subject was restrained by a 3-point belt, the collision velocity amounted 50 km/h, the mean sled deceleration was 15,3 g. At the left side of the Figure the bending angle of the head-neck unit as well as the angular velocity and the angular acceleration is shown.

The bending angle of the head-neck unit is reached 204 ms after the crash and amounts 84 degrees, the values of

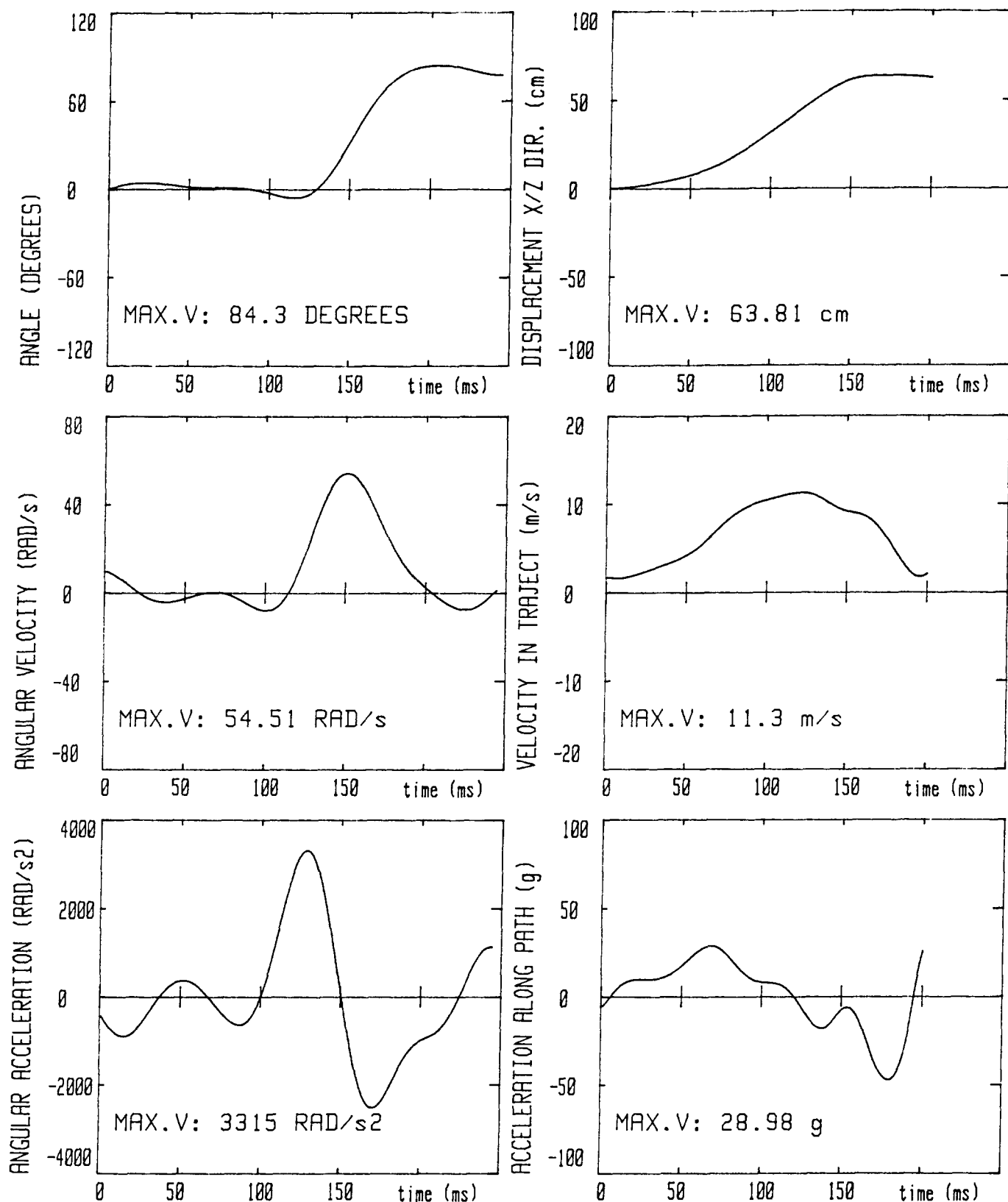


Fig. 5: Example of time-histories evaluated data from high speed film analysis for the head-neck unit and the head anatomical origin. Frontal collision, 50 km/h, $a = 15$ g, 3-point belt (Run No. 7915)

the angular velocity and angular acceleration correspondingly amount 55 rad/s and 3320 rad/s².

The right side of the Fig. 5 illustrates besides the resultant displacement of the anatomical origin of the head in x-/z-direction, the velocity in trajectory and the acceleration along the path of the same point. The maximum resultant displacement of the head's anatomical origin in x-/z-direction of 63,8 cm is reached about 170 ms after the crash, the velocity in trajectory and the acceleration along the path of the same head point correspondingly amounts 11,3 m/s and 29 g.

The maxima of all data evaluated by the film analysis for the frontal collision are summarized in Table 3. The evaluated values show scatterings which may be explained with different collision velocities, restraint systems and anthropometric data of the test subjects. Similar observations were also made for the data of the lateral collisions (Tab. 4).

Medical Findings

The evaluation of the vertebral column includes the region between C 1 and Th 4. 28 frontal and 15 lateral collision tests were investigated. Independent of the type of collision (frontal or lateral) following lesions of the cervical and upper thoracic spine were observed:

Vertebra

body	
facet	fracture (AIS 2, AIS 3)
transverse process	sprain (AIS 1)
spinous process	

ligaments

flavum	
posterior longitudinal	strain (AIS 1)
anterior longitudinal	laceration (AIS 2)
interspinal	

intervertebral discs

strain, laceration
(AIS 1, AIS 2)

intervertebral joints joint capsule

strain, subluxation
(AIS 1, AIS 2)

spinal cord laceration

(AIS 4, AIS 5)

epidural space muscles

strains (AIS 1)
strains (AIS 1)

Hemorrhages were interpreted as strains if lacerations could not be proved at the same time in the concerned structures (ligaments, discs, joints, muscles). Since the occurrence of hemorrhages post mortem depends on the particular state of the mechanically loaded tissue region, one cannot determine that, due to the lack of hemorrhages in a total of 6 cases in this study, the vertebral column really remained uninjured within the meaning of AIS 0; so that in a real accident with living occupants at least pains would occur at the same loading conditions and the

same individual injury tolerance. Therefore, in these post mortem tests one could not obtain a better quantitative rating of the AIS 1 injuries.

Contrary to this, lacerations of the ligaments and smaller fractures, also lacerations of the intervertebral discs can be more authentically registered than in real accidents. Such AIS injuries cannot be proved with conventional x-ray technique in all cases. Therefore, such AIS 2 injuries are frequently underrated in real accident collectives.

The region, type and severity of the observed spinal injuries is explained in the following chapters: According to the structure up to five (5) different injuries occurred in the same segment; in order to code the injuries a total of ten (10) possibilities was admitted for the investigated spinal column region (C 1 to Th 4).

Location of Injuries

Fig. 6 shows the absolute and relative frequency of the injuries according to the vertebral level for the frontal and side impact tests. According to the kind of collision different injury sites were observed. While in the frontal collision the main injury area concerns the cervico-thoracic transition (frequencies 13 % to 16 %), in the lateral collision even higher frequencies (16 % to 21 %) are observed in the region C 2 to C 6.

Types of Injuries

A total of 16 types of injuries were observed in the frontal and lateral collision collectives. All these types of injuries concern the vertebral column level and were illustrated in Fig. 7 a,b, furthermore, the relative frequency of the injury type for the region C 1 to Th 4 is given. Intervertebral disc hemorrhages occurred most frequently: about 20 % in the frontal collision and 55 % in the lateral collision. The second most frequently observed injury concerned the ligamenta flava for both collision directions. It is striking that for frontal collisions, the ligamenta flava injuries occurred most frequent at the C6-T1 level while the intervertebral body fractures occurred most frequently at the T2 level.

Injury Severity

In both collectives an injury severity of AIS 1 to AIS 5 was observed, however, AIS 5 and AIS 4 occurred each one time in the lateral and frontal collision tests (Fig. 8 a,b).

The injury severity of AIS 1 (strains) was the most frequent one (54 % frontal collision, 76 % side collision) and concerned all injured levels of the investigated vertebral column. The secondly frequent observed injury severity - about 39 % in the frontal collision and 18 % in the side collision - AIS 2 (most lacerations) is over-represented at the levels Th 1 and Th 2 for the frontal collision, while in the lateral collision, with the exception of C 3 and C 7, it is equable distributed at the cervical spine.

AIS 3 (fracture) occurred in the frontal collision at the level of the Th 1 to Th 4, while in the lateral collision only in one case a fracture at the level C 2 was observed.

RUN NUMBER	ANGLE (degr.)	ANGULAR VELOCITY (rad/s)	ANGULAR ACCELER. (rad/s ²)	DISPL. X-DIRECT. (cm)	DISPL. X/Z-DIRECT. (cm)	VELOCITY IN TRAJ. (m/s)	ACCELER. ALONG PATH (g)
7702	72.6	42.8	2470	54.70	69.08	11.660	20.95
7704	75.9	39.9	2310	48.94	59.64	9.479	17.33
7801	97.7	46.6	2310	49.79	54.10	8.841	16.16
7804	82.5	28.2	1190	47.42	58.35	8.311	14.14
7805	87.7	28.8	978	44.69	50.99	7.859	20.15
7911	53.4	40.8	2360	60.34	74.41	10.130	23.80
7912	69.5	33.0	2200	70.09	72.27	10.610	24.71
7915	84.3	54.5	3320	59.97	63.81	11.300	28.98
7916	102.0	43.6	2380	46.71	53.85	9.376	23.86
7917	59.9	52.9	3700	71.16	76.13	11.840	35.76
7918	62.4	62.6	4910	62.38	66.98	15.880	38.62
7919	58.8	33.7	2330	60.96	65.57	13.100	36.43
8001	77.6	54.2	3120	63.56	68.40	11.910	29.35
8002	97.9	41.0	1450	68.93	74.12	11.240	16.25
8006	86.2	33.9	1320	49.58	53.48	8.485	21.87
8618	86.0	25.1	935	35.47	48.91	8.289	21.18
8622	117.0	49.4	1950	19.67	45.44	8.373	19.32
8706	89.0	37.5	1763	15.65	34.00	6.238	13.98
8708	88.9	29.1	1220	.	.	.	.
8709	85.0	39.9	1560	18.78	41.87	7.829	18.51
8710	108.0	47.6	2090	17.33	34.60	6.307	16.27
8803	22.8	13.5	746	.	.	.	.
8808	58.3	60.7	4060	13.47	32.83	12.330	.
8824	17.4	7.6	416	.	.	.	.
8915	46.0	26.0	1140	52.18	54.24	9.720	19.78
9013	55.5	24.7	944	36.39	44.38	6.406	19.10

Table 3: Evaluated data from high speed film analysis for the head-neck unit and the head anatomical origin, frontal collisions

RUN NUMBER	ANGLE (degr.)	ANGULAR VELOCITY (rad/s)	ANGULAR ACCELER. (rad/s ²)	VELOCITY IN TRAJ. (m/s)	ACCELER. ALONG PATH (g)
8535	65.0	59.0	4560	10.520	40.05
8537	86.0	63.0	4500	12.220	66.59
8538	54.0	22.0	1310	6.270	19.87
8546	35.0	23.0	1710	4.027	17.71
8547	75.0	51.0	3150	7.584	28.18
8607	.	.	.	4.094	22.66
8825	58.0	23.5	810	9.409	13.98
8831	58.5	31.0	1460	11.730	25.82
8832	64.0	34.2	2050	10.510	13.86
8834	53.9	23.6	1000	6.947	12.76
8904	57.2	15.9	679	10.280	19.69
8905	26.9	7.9	559	10.830	26.67
8907	57.0	32.0	1610	10.570	17.54
8931	80.0	38.7	2601	9.920	14.75
8935	57.7	38.1	2090	.	.

Table 4: Evaluated data from high speed film analysis for the head-neck unit and the head anatomical origin, side collisions

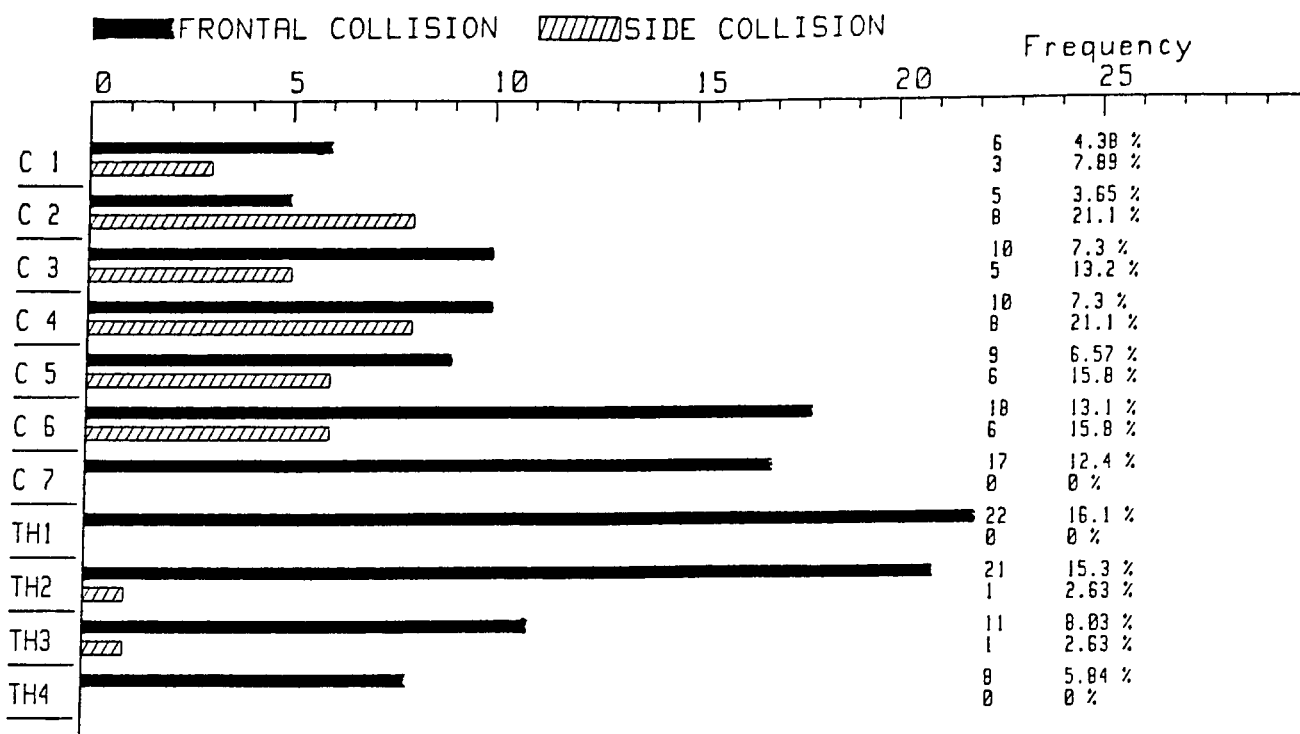


Fig. 6: Location of the vertebral column injuries according to the collision type

In 37 of 43 medically evaluated tests a kinematic analysis of the head-neck unit was also conducted (23 frontal and 14 side collisions). These evaluations are presented in the following chapters.

Dependencies of the existing data

Furthermore, a Spearman Rank Correlation was conducted with the available data. Tab. 5 shows the correlations between the anthropometric data, AIS severity and physical parameters for the frontal collision tests. As expected, high and significant correlations between the coherent physical parameters of the data evaluated from the film analysis were observed ($r = 0,89 - 0,49$). Also the continuous anthropometrical data show high and significant correlations ($r = 0,63 - 0,53$). The spine AIS has the highest correlation ($r = 0,58$) with the head maximum acceleration along the path, also with the maximum velocity in trajectory of the head ($r = 0,45$); the maximum angular acceleration and the maximum angular velocity show lower correlations ($r = 0,41, r = 0,36$) in regard to the spine injury severity. The AIS severity didn't correlate with the age.

In most of the data the correlations of the side collision collective are lower than the one in the frontal collision tests, therefore no table was made. Here too, the continuous data evaluated from the high speed films show high correlations among each other. Correlations between AIS severity and the evaluated physical parameters were not observed.

Physical Parameters and Injury Severity

Table 6 summarizes the mean values of the physical parameters and the AIS together with the upper and lower maximum value and some statistical magnitudes. All physical parameters show higher mean maxima values in the frontal collision than in the side collision; with exception of the maximum head acceleration along the path which lies in the mean higher in the lateral collisions than in the frontal collision. The comparison of the near-side and far-side occupant results in mean maxima values for all physical parameters, and show that higher values are reached for the near-side against the far-side occupant (Table 7), angular velocity and angular acceleration are significant; with exception of the velocity in trajectory of the head which lies in the mean higher in the far-side occupants than in the near-side occupants.

All the values show a big scatter for the frontal as well as for the side collision. According to the film analysis it is reached after previous extension of the neck by axial load, before a chin impact occurs (frontal collision) or lateral head impact against the shoulder (side collision).

An investigation of the bending angle in regard to the sex in the frontal collision resulted in the average for the female test subjects in a 23° significant higher angle than for the male test subjects (male 73° , female 96°).

Fig. 9 shows the dependence of the AIS severity according to the angular velocity for the investigated frontal collision collective with the regression straight line and the 90 % confidence interval; a big scattering of the values is observed. The evaluated spearman correlation coefficient amounts 0,36.

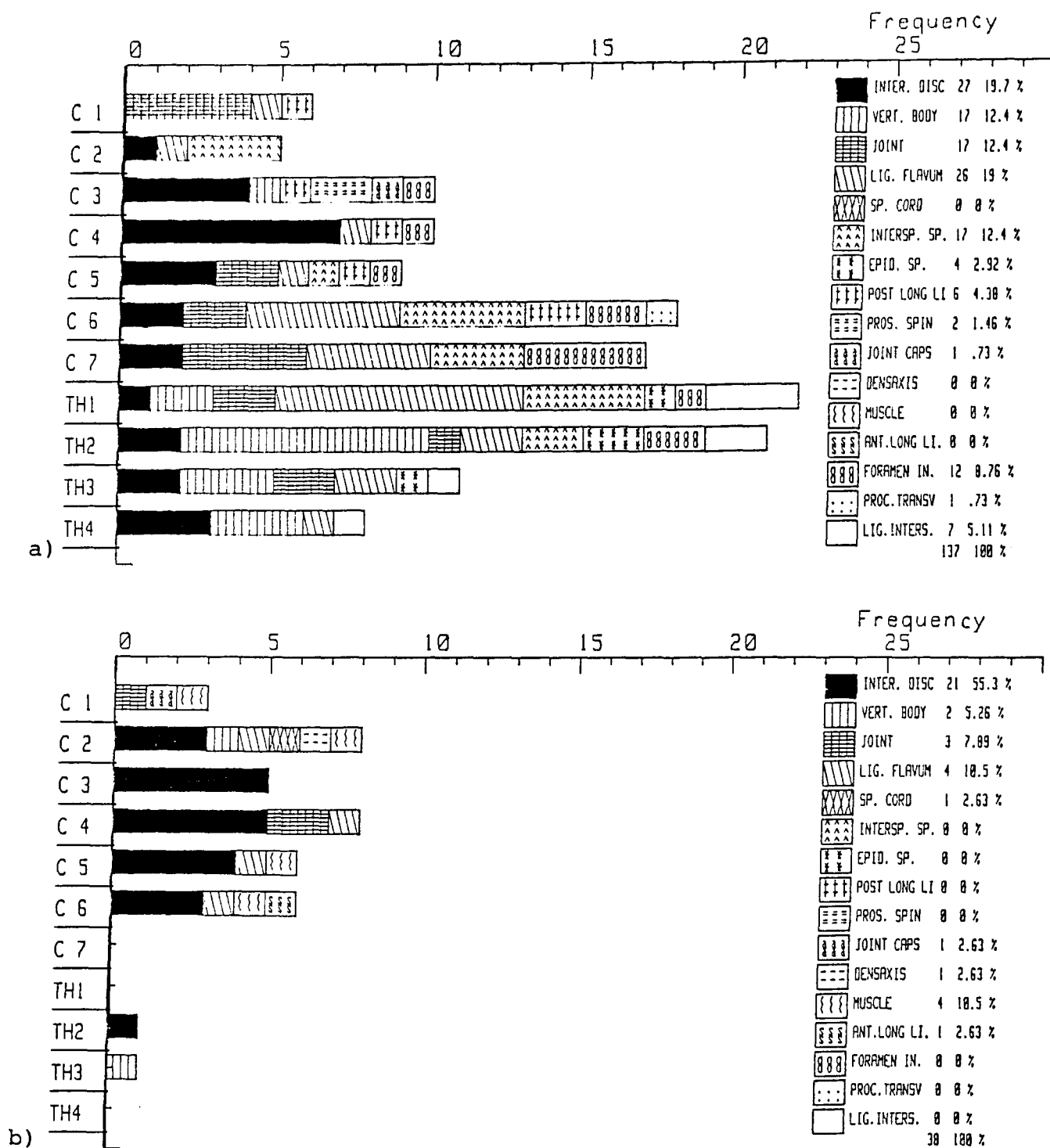


Fig. 7: Location of the vertebral column injuries according to the type.

a) Frontal collision

b) Side collision

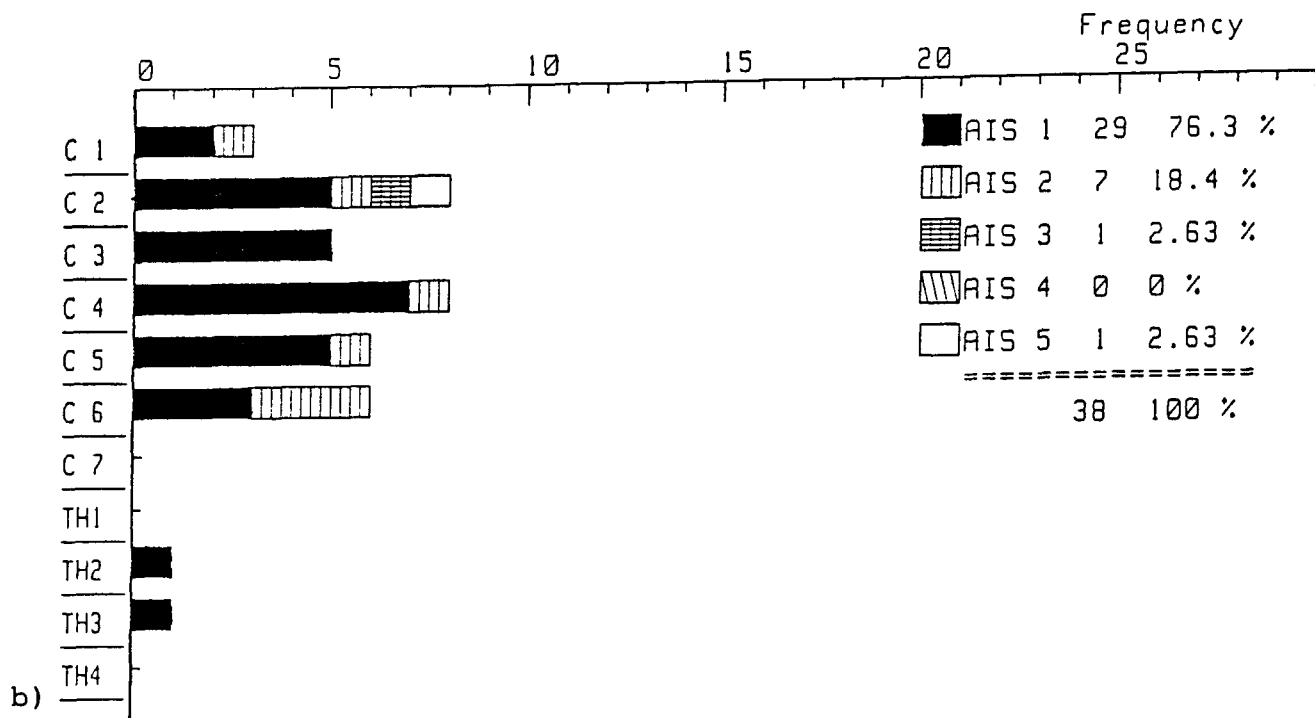
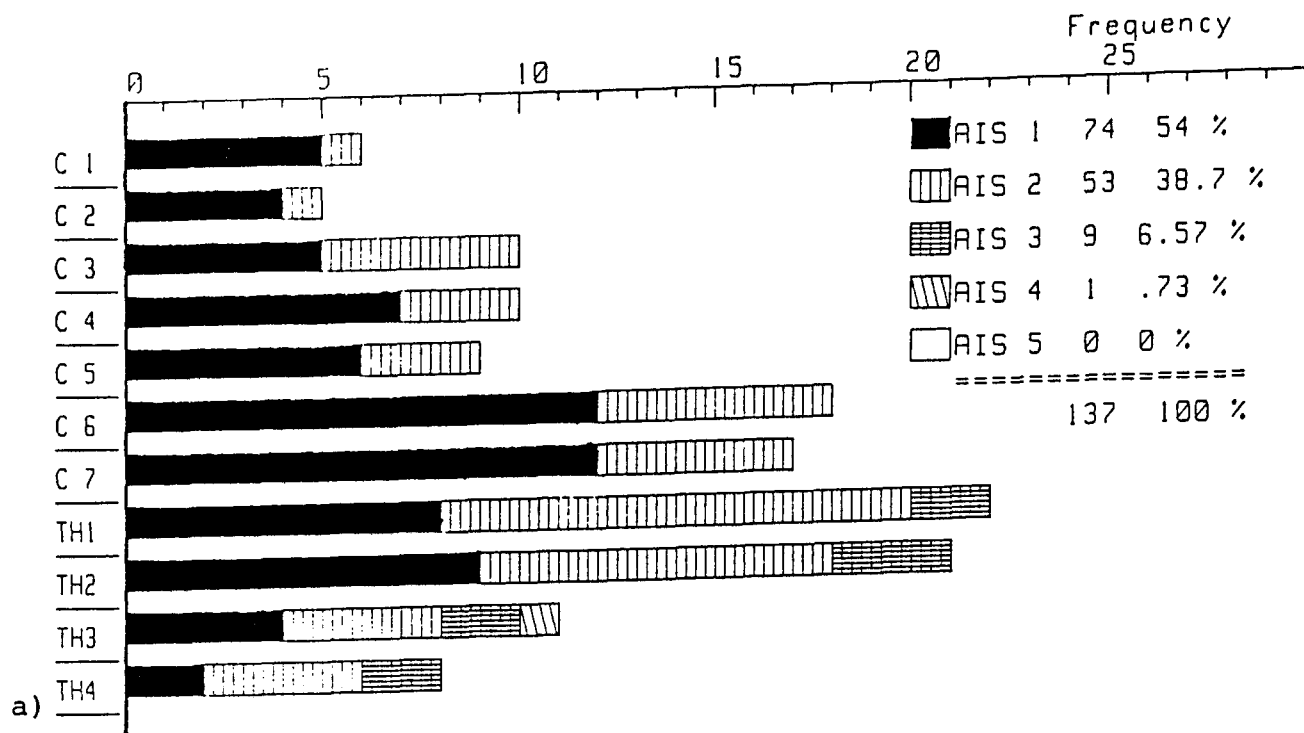


Fig. 8: Location of the vertebral column injuries according to the AIS-severity.

a) Frontal collision

b) Side collision

AGE	HEIGHT	WEIGHT	HAT SIZE	NECK CIRC.	HEAD-SH. DIST.	MAX. ANGLE	MAX. ANG. VELOCITY	MAX. ANG. ACCELER.	MAX. VELO. IN TRAJ.	MAX. ACCEL. ALONG PATH	SP-AIS
1.00000	-0.15758	0.14354	0.37427	0.23016	-0.55958	-0.09281	-0.61072	-0.58400	-0.33655	-0.13292	0.12405
0.0	0.3972	0.4411	0.0381	0.2129	0.0013	0.6520	0.0009	0.0017	0.1164	0.5554	0.5061
-0.15758	1.00000	0.53694	-0.02422	0.21504	0.25912	-0.10793	0.10538	0.09698	0.10310	-0.14788	-0.25517
0.3972	0.0	0.0018	0.8971	0.2453	0.1668	0.5997	0.6084	0.6374	0.6397	0.5113	0.1659
0.14354	0.53694	1.00000	0.47810	0.63714	0.01087	-0.27133	-0.24396	-0.15916	0.08722	0.05892	-0.24427
0.4411	0.0018	0.0	0.0065	0.0001	0.9545	0.1800	0.2297	0.4374	0.6923	0.7945	0.1854
0.37427	-0.02422	0.47810	1.00000	0.48629	-0.19090	-0.34069	-0.35591	-0.31818	-0.22926	0.03989	-0.24726
0.0381	0.8971	0.0065	0.0	0.0055	0.3123	0.0885	0.0743	0.1132	0.2927	0.8601	0.1799
0.23016	0.21504	0.63714	0.48629	1.00000	0.08313	-0.39705	-0.33843	-0.24781	-0.08890	-0.04707	-0.26165
0.2129	0.2453	0.0001	0.0055	0.0	0.6623	0.0446	0.0908	0.2222	0.6867	0.8352	0.1551
-0.55958	0.25912	0.01087	-0.19090	0.08313	1.00000	0.03567	0.35032	0.26053	0.23602	-0.17124	-0.16093
0.0013	0.1668	0.9545	0.3123	0.6623	0.0	0.8656	0.0860	0.2085	0.2903	0.4580	0.3956
-0.09281	-0.10793	-0.27133	-0.34069	-0.39705	0.03567	1.00000	0.31424	0.03248	-0.49802	-0.45567	0.05275
0.6520	0.5997	0.1800	0.0885	0.0446	0.8656	0.0	0.1180	0.8748	0.0156	0.0331	0.7980
-0.61072	0.10538	-0.24396	-0.35591	-0.33843	0.35032	0.31424	1.00000	0.89347	0.52187	0.31742	0.35926
0.0009	0.6084	0.2297	0.0743	0.0908	0.0860	0.1180	0.0	0.0001	0.0106	0.1500	0.0715
-0.58400	0.09698	-0.15916	-0.31818	-0.24781	0.26053	0.03248	0.89347	1.00000	0.75414	0.58515	0.41956
0.0017	0.6374	0.4374	0.1132	0.2222	0.2085	0.8748	0.0001	0.0	0.0001	0.0042	0.0329
-0.33655	0.10310	0.08722	-0.22926	-0.08890	0.23602	-0.49802	0.52187	0.75414	1.00000	0.72558	0.45319
0.1164	0.6397	0.6923	0.2927	0.6867	0.2903	0.0156	0.0106	0.0001	0.0	0.0001	0.0299
0.13292	-0.14788	0.05892	0.03989	-0.04707	-0.17124	-0.45567	0.31742	0.58515	0.72558	1.000	0.58130
0.5554	0.5113	0.7945	0.8601	0.8352	0.4580	0.0331	0.1500	0.0042	0.0001	0.0	0.0045
0.12405	-0.25517	-0.24427	-0.24726	-0.26165	-0.16093	0.05275	0.35926	0.41956	0.45319	0.58130	1.00000
0.5061	0.1659	0.1854	0.1799	0.1551	0.3956	0.7980	0.0715	0.0329	0.0299	0.0045	0.0

Table 5: Spearman Rank Correlation of the evaluable data with significance niveau, frontal collision

SIDE COLLISION

	N	MEAN	MAX	MIN	STD	STD/MEAN	VAR	V-COEFF.
SP-AIS	15	1.20	5.00	0.00	1.15	0.30	1.31	95.54
MAX.ANGLE	14	59.16	86.00	26.90	15.58	4.16	242.63	26.33
MAX.ANG. VELOCITY	14	33.06	63.00	7.90	15.90	4.25	252.84	48.09
MAX.ANG. ACCELER.	14	2006.36	4560.00	559.00	1293.14	345.61	1672220	64.45
MAX.VELO. IN TRAJ.	14	8.92	12.22	4.03	2.68	0.72	7.17	30.02
MAX.ACCEL. ALONG PATH.	14	24.29	66.59	12.76	14.23	3.80	202.47	58.57

FRONTAL COLLISION

	N	MEAN	MAX	MIN	STD	STD/MEAN	VAR	V-COEFF.
SP-AIS	31	1.65	4.00	0.00	1.02	0.18	1.04	61.89
MAX.ANGLE	26	74.70	117.00	17.40	23.97	4.70	574.45	32.08
MAX.ANG. VELOCITY	26	38.37	62.60	7.60	13.54	2.65	183.21	35.28
MAX.ANG. ACCELER.	26	2045.08	4910.00	416.00	1091.54	214.07	1191458	53.37
MAX.DISPL. X/Z-DIRECT.	23	56.41	76.13	32.83	13.43	2.80	180.37	23.81
MAX.VELO. IN TRAJ.	23	9.80	15.88	6.24	2.38	0.50	5.68	24.31
MAX.ACCEL. ALONG PATH.	22	22.57	38.62	13.98	7.14	1.52	50.92	31.62

Table 6: Mean values of the physical parameters, the AIS-severity and some statistic magnitudes for the frontal and side collision tests

SIDE COLLISION

----- POS=N -----

	N	MEAN	MAX	MIN	STD	STD/MEAN	VAR	V-COEFF.
SP-AIS	7	0.86	1.00	0.00	0.38	0.14	0.14	44.10
MAX.ANGLE	6	62.12	86.00	35.00	17.69	7.22	313.08	28.49
MAX.ANG. VELOCITY	6	42.68	63.00	22.00	17.80	7.27	316.88	41.71
MAX.ANG. ACCELER.	6	2886.67	4560.00	1310.0	1412.61	576.70	1995467	48.94
MAX.VELO. IN TRAJ.	6	7.45	12.22	4.03	3.36	1.37	11.31	45.13
MAX.ACCEL. ALONG PATH.	6	32.51	66.59	17.71	18.51	7.56	342.58	56.93

SIDE COLLISION

----- POS=F -----

	N	MEAN	MAX	MIN	STD	STD/MEAN	VAR	V-COEFF.
SP-AIS	8	1.50	5.00	0.00	1.51	0.53	2.29	100.79
MAX.ANGLE	8	56.94	80.00	26.90	14.62	5.17	213.84	25.68
MAX.ANG. VELOCITY	8	25.85	38.70	7.90	10.22	3.61	104.43	39.53
MAX.ANG. ACCELER.	8	1346.13	2601.00	559.00	719.58	254.41	517800.4	53.46
MAX.VELO. IN TRAJ.	8	10.02	11.73	6.95	1.42	0.50	2.00	14.12
MAX.ACCEL. ALONG PATH.	8	18.13	26.67	12.76	5.48	1.94	30.08	30.25

Table 7: Mean values of the physical parameters, the AIS-severity and some statistic magnitudes for the side collision tests according to the sitting position

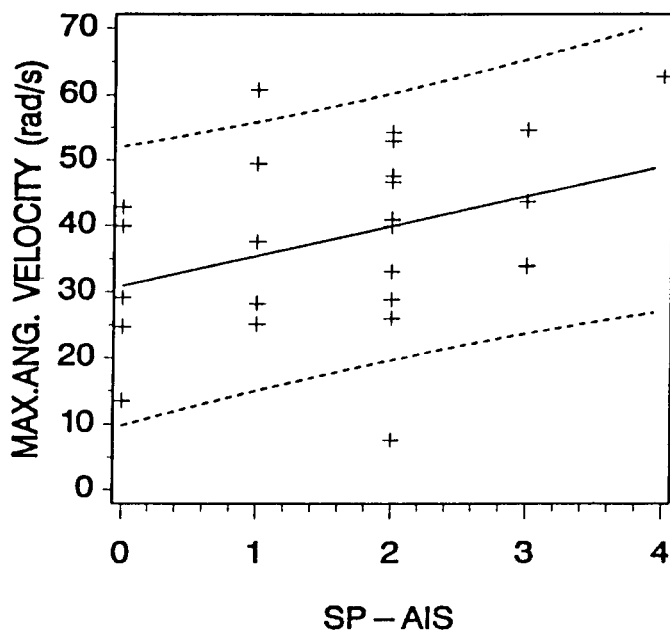


Fig. 9: Frontal collision. Neck angular velocity AIS severity ($y = 4,17 x + 32,7$, $r = 0,36$)

In Fig. 10 the dependence of the AIS severity according to the angular acceleration for the frontal collision tests with the evaluated regression line and the 90 % confidence interval is illustrated. These two parameters show a little higher correlation ($r = 0,42$) than the angular velocity, however also big scatterings were observed. Acceleration values of 950 to 1000 rad/s^2 could lead to AIS 1 or AIS 2, at this value however, the cervical and upper thoracic spine remains uninjured in the frontal collision. An injury severity of AIS 3 up to 1320 rad/s^2 was observed in the frontal impact. In one case with an AIS 4 (cord laceration C 4, unstable segment) the angular acceleration value amounted 4910 rad/s^2 .

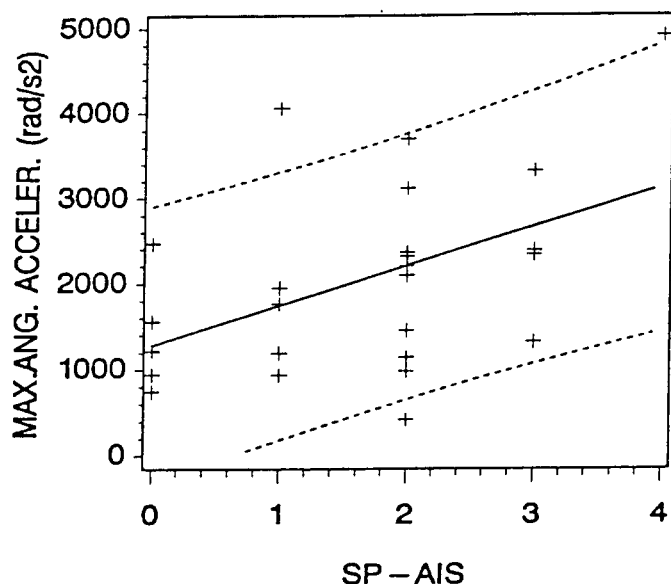


Fig. 10: Frontal collision. Neck angular acceleration AIS severity ($y = 510 x + 1195$, $r = 0,42$)

The dependence of AIS severity with respect to the velocity in trajectory of the head along with the regression line and the 90 % confidence interval is illustrated in Fig. 11. The velocity in trajectory of the head shows a higher correlation ($r = 0,45$) as the angular velocity and acceleration with the injury severity of the neck.

The highest correlation ($r = 0,58$) with the spine AIS was obtained with the head acceleration along the path (Fig. 12).

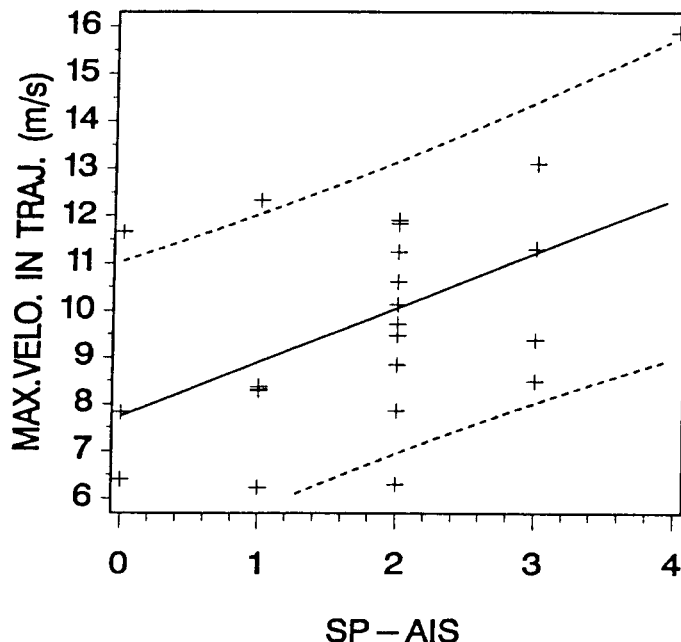


Fig. 11: Frontal collision. velocity in trajectory of the head AIS severity of the neck ($y = 1,28 x + 7,36$, $r = 0,45$)

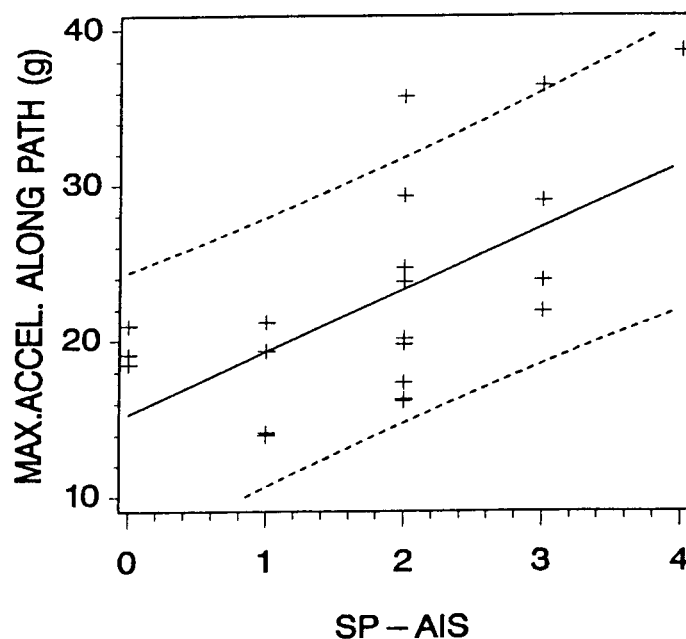


Fig. 12: Frontal collision. Head acceleration along the path AIS severity ($y = 3,99 x + 15,3$, $r = 0,58$)

DISCUSSION

Forty-three (43) frontal and side collision tests with restrained post mortem human subjects were investigated in regard to the type, severity and location of the vertebral column injuries between C 1 and Th 4. The subjects were protected by the conventional 3-point standard belt or additionally with a pretensioner or with a double shoulder lap V-pelvic belt and finally by a 3-point belt with an inboard anchored shoulder belt. The Δv was 30 km/h, 50 km/h and 60 km/h in the frontal collision and 25 km/h, 30 km/h and 35 km/h in the side collision. The side collision collective included far-side and near-side occupants.

In 37 tests a kinematical analysis of the head-neck region was made using the high-speed films. The head-neck angles were determined; the angular velocity and angular acceleration were evaluated, furthermore the displacement of the head, in x-z-direction for the frontal collision tests, the velocity in trajectory of the head and the head acceleration along the path for both collision types were evaluated.

Because of the great variety of restraint systems used in the tests comprising the data collective, only parameters obtained from the analysis of the head kinematics were used to study injury relationships.

The observed injuries at the vertebral column differ in regard to location, type and severity between the two investigated collision types. While in the frontal collision the main injured area concerns the cervico-thoracic transition, in the side collision it is related to the middle of the cervical spine. Also severe injuries occurred in the frontal collision confirming our former experiences and they could have been avoided by using a restraint system combined of 3-point belt and airbag (8). The injury severity of vertebral column injuries in the side collision turned out minor and this is confirmed by our experience and by other authors (3).

Head-neck responses and their results were often a matter of interest and most tests were conducted with volunteers and comparison tests were made with cadavers. The pain level (AIS 1) was scheduled as the tolerance limit of the cervical spine. As loading magnitude the moment about the occipital condyles was used (16) and additionally rotation and angular acceleration (3, 21), whereby head-neck has to be considered as a correlated unit. Our results show that AIS 1 (pains) occur at an angle of 58° for frontal collisions and 27° for lateral collisions. Considering that our collective included not only young people as in the volunteer tests, but also old subjects, this observation doesn't contradict the statements of Mertz and Patrick (16) and Bendjellal et al. (3).

Also the limits in regard to the angular velocity and angular acceleration which were observed in the frontal collision of 8 rad/s up to 63 rad/s and 950 rad/s² up to 4000 rad/s² and in the side collision of 8 rad/s up to 63 rad/s and 550 rad/s² up to 4560 rad/s² AIS 1 (strains = pains) are in correlation with the results of Ewing et al. (5) and Bendjellal et al., (3).

The angle as well as the angular velocity and the angular acceleration show great scatterings in the injury severity. This is understandable due to the complex

kinematic and the inhomogenous structure of the cervical- and upper thoracic vertebral column which makes it more difficult to observe a neck injury criterion.

Higher correlations with the AIS severity of the neck show the velocity in trajectory of the head ($r = 0,45$) and the head acceleration along the path ($r = 0,58$) in regard to the angular velocity ($r = 0,36$) and the angular acceleration ($r = 0,42$). That means, the head acceleration along the path and the velocity in trajectory are more suitable parameters than the angular velocity and the angular acceleration in order to describe the AIS severity of the neck.

CONCLUSIONS

Location and severity of neck injuries in belt-protected occupants significantly differ in frontal and side collisions.

Because of the complex kinematic and the inhomogenous vertebral column structure the observation of a neck injury criterion is complicated.

The highest correlation with the neck injury severity shows the head acceleration along the path ($r = 0,58$).

Minor injuries (AIS 1, strains = pains) were observed in the frontal collision at a head acceleration along the path of 18,5 to 20,9 g. Above the value of 21 g none of the cases remained uninjured. This acceleration was sufficient for serious neck injuries (AIS 3) in a few cases. On the other hand accelerations up to 35 g were tolerated without the occurrence of a higher injury severity than AIS 2.

For the definition of a finalized injury criterion of the neck a more extensive test collective is required.

The influence of anthropometric parameters, especially the age in regard to the injury severity as well as the kinematic couldn't be presented in that kind as it would be expected according to traumatologic experience for the investigated collective.

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