COMPARISON OF THREE - POINT BELT - AND AIR BAG - KNEE BOLSTER SYSTEMS. INJURY CRITERIA AND INJURY SEVERITY AT SIMULATED FRONTAL COLLISIONS

by

D. Kallieris, R. Mattern and G. Schmidt

University of Heidelberg

G. Klaus, Volkswagenwerk AG

ABSTRACT

Cadavertests have been performed on a decelerating sled in two series of frontal impact simulation with a crash velocity of 50 km/h and a mean deceleration of 20 g. The first series involves 32 tests with 3-point belt protected subjects, the second series 12 tests with air bag - knee bar protected occupants in passenger position. The age of the subjects ranged from 12 - 71 years. The HIC-mean values of the three-point protected subjects amounted to 645, and for the air bag - knee bar tests 449. The scatter and the standard deviation are obviously higher at the air bag - knee bar tests than at the 3-point belt tests. The analysis of the head accelerations shows at the 3-point belt tests the highest values in z-direction, in the air bag - knee bar tests in x-direction. In the 3-point belt tests an average of 8 rib fractures occurred, in the air bag - knee bar tests an average of 4 rib fractures; the scatter at the air bag - knee bar tests was higher. The overall injury severity was determined to be an average of MAIS 2-3, thus tending to be slightly lower than in the 3-point belt tests (MAIS 3).

INTRODUCTION

For the present time, most automobile safety experts throughout the world consider the three-point belt to be the most effective safety device available to protect vehicle occupants during collisions.

In many countries it is compulsory to wear safety-belts (6)*, however, the belt wearing rate differs in each country, i.e. in the Fed. Rep. of Germany it amounts somewhat

*Numbers in the parentheses designate References at the end of paper over 50 percent, in the USA about 10 percent. For this reason, thoughts should be made on passive restraint systems. The American authority demanded the use of passive restraint systems by publishing a draft of a bill in 1969; nine years later "occupant crash protection" passed into a law. In October 1981 the regulation was cancelled. At the beginning of the legislation it was officially emphasized that the legislator does not dictate a certain passive system, however, leading officials of the security authority always considered the "air-bag" system to be the only technical solution.

In the meantime passive restraint systems have been developed and experimentally tested (1, 5).

A limited number of these systems has been installed in vehicles used in real road traffic. Therefore, it was possible to already test the effectiveness of such passive systems in road accidents (8, 10).

In this paper, own cadaver tests conducted by using three-point standard belt and air bag-knee bar system will be compared related to the loading, kinematic and injury severity.

TEST METHOD

The tests have been performed on a deceleration sled - the sled is stopped by means of deforming a metal band - the pulse shape is trapezoidal. The collision velocity amounts 49-51 km/h, the sled deceleration 18-22 g.

a) THREE-POINT BELT TESTS

The driver and front car passenger positions have been simulated. A VW-beetle type I seat and a three point retractor belt have been mounted on the sled. The anchorage points of the belt did not correspond to a certain type of car, but lay within the variation range of European cars. The upper anchorage point and the seat position were, independent of the size of the test subject, the same at each test. Only the foot rest was adjusted to the length of the test subject in each test (Fig. 1).

b) AIR BAG KNEE BAR TESTS

The front car passenger position has been simulated. When conducting the tests the front half of a passenger compartment of a VW-Golf has been used, mounted on the sled (Fig. 2). A VW-Golf seat was used. A combination of passenger air bag and knee bar served as restraint system. The seat position was so adjusted that the distance between knee and knee bar amounted 8 cm in each test.

High speed films have been taken of frontal and side view. Photos were taken before and after the test.

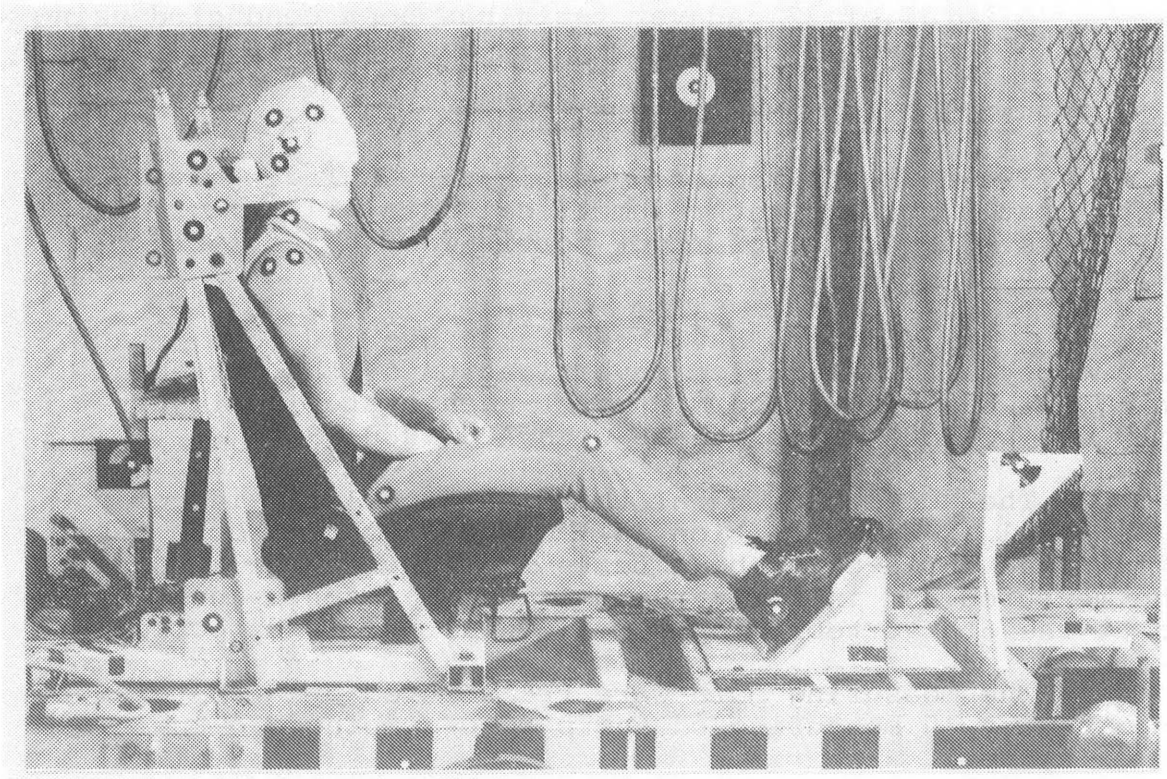

Fig. 1 : Side view of test configuration, 3-point belt system

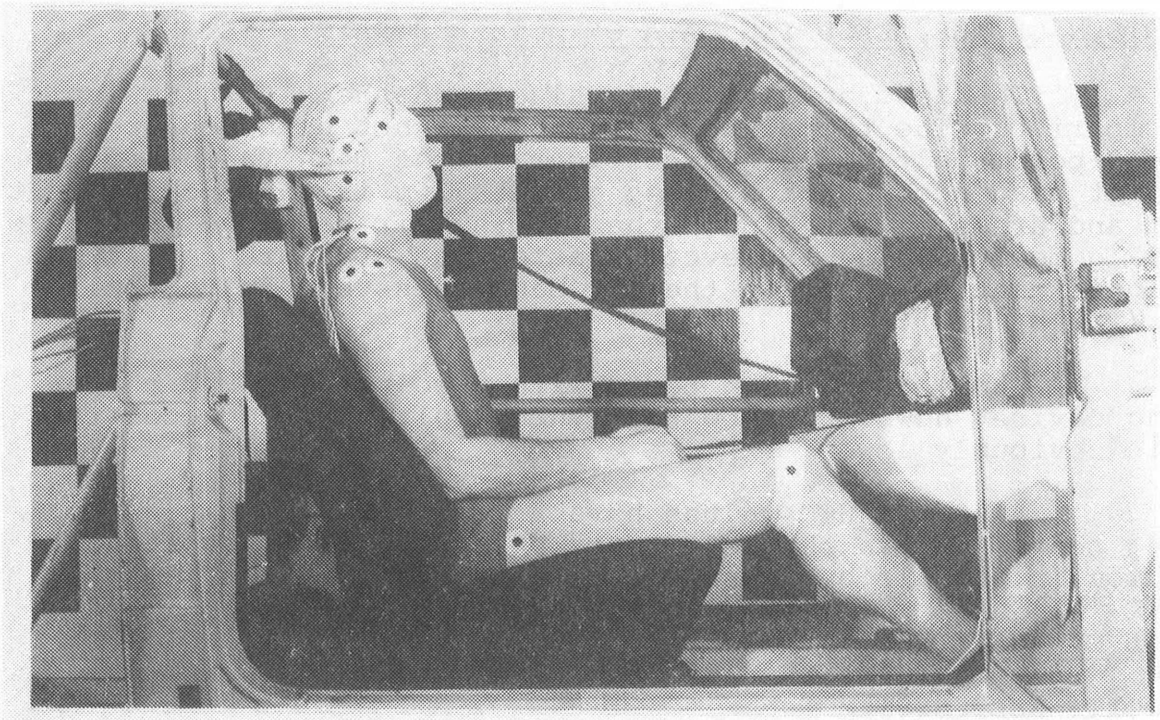

Fig. 2 : Side view of test configuration, air bag-knee bar system

A total of 32 cadaver tests has been conducted using three-point belts and 10 tests using air bag - knee bar systems.

CADAVER PREPARATION AND INSTRUMENTATION

Fresh unembalmed cadavers in varying ages have been used. The most important anthropometrical data will be given under Results. The degree of rigor mortis was subjectively established.

X-ray pictures have been taken pre and post impact. A full autopsy with a detailed investigation of the vertebral column (7, 4) has been performed after each test. The injury severity was scaled in accordance with AIS 1980 (9).

The acceleration at the right and left side of the head, bi-axial (x-, z-direction (3)) was measured in both test series. In the three-point belt tests the shoulder belt force will be measured and in the air bag - knee bar tests the acceleration at the 6th vertebral body - bi-axial (x-, z-direction).

The measuring data were transmitted by a FM-telemetry system; thereby 10 measuring channels were combined to one multiplex system.

The evaluation of the measuring data was conducted in the Volkswagenwerk by a process computer.

COMPARISON OF THE MEASURING DATA OF BOTH RESTRAINT SYSTEMS

The head acceleration values and the HIC values suit for comparison. The thorax acceleration has not been measured in the 3-point belt tests. In considering the mean values of the resultant head acceleration, they amount 72 g in the 3-point belt system and are somewhat higher than in the air bag-knee bar tests with 67 g medium value. However, scatter and standard deviations are significantly higher in the air bag tests than in the belt tests (Table 1, 2).

Dummy comparison tests with 3-point belt and a pre-loading device, however, show that the resultant head acceleration is obviously lower.

Also the HIC values have a lower mean value in the air bag tests than in the belt tests; here too a higher standard deviation in the air bag tests is determinable.

MEDICAL EVALUATION

a) 3-POINT BELT SYSTEM

Table 3 shows the most important anthropometrical data of the test subjects, the number of rib fractures, the injury severity of thorax, abdomen and spinal column, the MAIS as well as the most important statistical data of the results. According to the age of the test subjects 0 up to 23 rib fractures occurred. The AIS thorax varies between 0 and 4 and is predominantly determined by the number of rib fractures. Also the AIS values of abdomen and spinal column are found to be in the same range as those of the thorax.

b) AIR-BAG KNEE-BAR SYSTEM

Table 4 states the most important anthropometrical data, number of rib fractures, injury severity for head, thorax, spinal column, extremities and MAIS. In the test subjects 0 up to 20 rib fractures have been observed. The AIS thorax, predominantly determined by the number of rib fractures, like in the 3-point belt tests, amounted between 0 and 4.

Except for one case (skin abrasion AIS 1), no injury of the abdomen was observed. The injury severity of the spinal column is in the same range as the one of the thorax. In one case, bridging vein injuries (AIS 4) have been observed, the HIC value amounted 506. In 2 cases we found fractures of the extremities (upper thigh fracture, tibia with bursting open of the eminentia intercondylica).

Two cases are not shown in Table 4, as the air-bag did not inflate because of a technical failure. Nevertheless, the comparison of these two tests without an effective restraint system with those tests having a working one, seems to be interesting, because the effectiveness of the restraint device is here especially significant. In the first case, the test subject is a 71-year old male, who has suffered a nasal bone fracture, a sternum fracture, 11 rib fractures, as well as several spinal column injuries. The spinal column injuries led to a MAIS 5, they consisted of intervertebral disengagements between the neck segments C6 and C7, as well as the thorax segments Th4/Th5.

In the 2nd case, in a 20-year old female, facial skin injuries occurred, further laceration of the right carotid artery, 1 cm above the aorta arc, a liver rupture, as well as a cervical spine intervertebral disengagement between C5/C6; this also corresponds to a MAIS 5.

COMPARISON OF THE INJURY SEVERITY OF BOTH SYSTEMS

According to general experience, the injury severity very much depends of the age of the test subjects. In our two collectives, the age mean value of the 3-point belt tests amounts 35 years, in the air bag tests the average age of the test subjects was 44 years. Assuming that both restraint systems would have the same effectiveness, one would expect a higher average injury severity in the air bag tests. This could not be confirmed in the tests conducted by us.

Run No.	Sex	Age (Years)	Body mass (kg)	Body length (cm)	Shoulder belt force (N)	Head Res. Accel. (g)	HIC
1	F	71	45	155	4805	-	-
2	M	65	87	186	6671	-	-
3	M	45	81	182	7063	-	-
4	F	65	69	155	5886	-	-
5	M	36	70	180	5690	-	-
6	M	39	76	175	7004	81,0	715
7	F	22	52	160	5248	72,0	759
8	M	14	58	166	5788	85,0	936
9	F	32	53	163	5562	83,0	804
10	M	29	69	175	6661	82,0	1008
11	M	23	76	183	7220	75,0	805
12	M	16	68	182	5925	110,0	537
13	M	45	75	159	7446	76,0	628
14	F	15	44	168	5052	83,0	663
15	F	54	60	166	6033	62,0	681
16	M	20	76	178	7122	70,0	785
17	F	26	55	166	5484	60,0	584
18	F	22	48	163	5680	66,0	600
19	M	25	61	172	5925	68,0	600
20	F	26	54	156	5572	81,0	426
21	M	21	56	169	6259	63,0	540
22	M	20	67	173	5474	54,0	407
23	M	12	41	147	4807	67,0	502
24	M	45	62	164	6259	77,0	812
25	M	22	89	192	7534	60,0	847
26	F	55	66	164	8348	58,0	406
27	M	55	81	163	9879	60,0	431
28	F	53	57	159	7220	55,0	353
29	F	37	49	155	5798	90,0	924
30	M	22	71	182	7289	72,0	699
31	M	43	71	161	7819	50,0	365
32	M	49	82	178	7416	71,6	589
Mean		35	65	169	6439	71,6	645
STD Dev.		16,7	12,9	10,9	1115	13,1	184,1
Min.		12	41	147	4807	50,0	353
Max.		71	89	192	9879	110	1008

Table 1: 32 three-point belt tests, impact velocity 50 km/h, sled deceleration 18 - 22 g, important anthropometrical data, measured and evaluated physical data including some descriptive statistics.

Run No.	Sex	Age (Years)	Body mass (kg)	Body length (cm)	Head Res. Accel. (g)	HIC	Th Res. Accel. (g)
1	F	66	75	170	32.5	113.7	39.1
2	M	66	93	177	-	-	-
3	M	26	64	172	51.6	308.6	67.1
4	M	34	64	174	-	-	-
5	M	65	73	178	59.1	436.4	76.1
6	M	26	74	180	137.9	866.5	75.1
7	M	43	85	191	97.0	506.1	53.6
8	M	37	62	167	54.1	379.4	63.1
9	M	18	69	176	37.9	154.6	45.4
10	M	55	71	177	62.5	823.0	44.0
Mean		44	73	176	66.6	448.6	57,9
STD Dev		18.3	9.7	6.5	34.7	278.0	14.4
Min.		18	62	167	32.5	113.7	39.1
Max.		66	93	191	137.9	866.5	76.1

Table 2: 10 air bag - knee bar tests, impact velocity 50 km/h, sled deceleration 18 - 22 g, important anthropometrical data, measured and evaluated physical data including some descriptive statistics.

In the 3-point belt tests an average of 8 rib fractures occurred. The regional AIS values of thorax, abdomen and spinal column were between 2 and 3, the MAIS amounted 3; each time the average of the collective.

Opposite to this, in the average only 3-4 rib fractures were found in the air bag tests; the regional AIS values of the thorax amounted 1-2, of the spinal column 2, the MAIS amounted 2-3.

In the air bag tests it appears there is a lower tendency in regard to the injury severity than in the 3-point belt tests, although because of the age structure in the air bag collective one expected a contrary result.

Run	Sex	Age (Years)	Body mass (kg)	Body length (cm)	Number Rib Fract.	AIS			MAIS
						Thorax	Abdomen	Vertebr. Col.	
1	F	71	45	155	18	3	5	3	5
2	M	65	87	186	15	4	3	4	4
3	M	45	81	182	16	4	4	2	4
4	F	65	69	155	23	4	3	3	4
5	M	36	70	180	13	4	3	2	4
6	M	39	76	175	16	4	3	5	5
7	F	22	52	160	1	2	1	2	2
8	M	14	58	166	0	0	1	2	2
9	F	32	53	163	6	2	3	1	3
10	M	29	69	175	4	2	2	1	2
11	M	23	76	183	0	2	2	-	2
12	M	16	68	182	0	1	1	-	1
13	M	45	75	159	8	3	4	3	4
14	F	15	44	168	0	1	5	3	5
15	F	54	60	166	10	3	1	3	3
16	M	20	76	178	5	2	1	3	3
17	F	26	55	166	1	2	1	2	2
18	F	22	48	163	0	0	-	-	0
19	M	25	61	172	16	3	1	3	3
20	F	26	54	156	3	2	3	3	3
21	M	21	56	169	3	3	3	2	3
22	M	20	67	173	5	2	4	3	4
23	M	12	41	147	0	1	1	0	1
24	M	45	62	164	11	3	2	3	3
25	M	22	89	192	0	1	1	2	2
26	F	55	66	164	16	4	1	4	4
27	M	55	81	163	16	4	4	4	4
28	F	53	57	159	15	3	0	3	3
29	F	37	49	155	21	4	1	3	4
30	M	22	71	182	2	2	0	2	2
31	M	43	71	161	1	2	0	2	2
32	M	49	82	178	14	4	3	2	4
Mean		35	65	169	8	(2,5)	(2,2)	(2,6)	3
STD Dev		16,7	12,9	10,9	(7,4)	(1,2)	(1,5)	(1,0)	(1,2)
Min.		12	41	147	0	0	0	0	0
Max.		71	89	192	23	4	5	5	5

Table 3: 32 three-point belt tests, impact velocity 50 km/h, sled deceleration 18 - 22 g, important anthropometrical data, number of rib fractures, regional AIS and MAIS, including some descriptive statistics. (Mean values and standard deviations are at ordinal scaled data as AIS strictly speaking not defined. They have to be interpreted only as valuation).

Run No.	Sex	Age (Years)	Body mass (kg)	Body length (cm)	Number Rib Fract.	AIS				MAIS
						Head	Thorax	Vertebr. Col.	Extr.	
1	F	66	75	170	0	0	0	3	0	3
2	M	66	93	177	1	0	1	4	0	4
3	M	26	64	172	0	0	0	0	0	0
4	M	34	64	174	20	0	4	2	3	4
5	M	65	73	178	10	0	3	4	0	4
6	M	26	74	180	0	0	0	2	0	2
7	M	43	85	191	3	4	2	1	3	4
8	M	37	62	167	0	0	0	2	0	2
9	M	18	69	176	0	0	0	1	0	1
10	M	55	71	177	2	0	1	1	0	1
Mean		44	73	176	3,6	(0,4)	(1,1)	(2,0)	(0,6)	(2,6)
STD Dev		18,3	9,7	6,5	(6,5)	(1,3)	(1,4)	(1,3)	(1,3)	(1,3)
Min.		18	62	167	0	0	0	0	0	1
Max.		66	93	191	20	4	4	4	3	4

Table 4: 10 air bag - knee bar tests, impact velocity 50 km/h, sled deceleration 18 - 22 g, important anthropometrical data, number of rib fractures, regional AIS and MAIS including some descriptive statistics.(Mean values and standard deviations are at ordinal scaled data as AIS strictly speaking not defined. They have to be interpreted only as valuation).

COMPARISON OF THE INJURY PATTERN

When analysing the injury severity, it already was noticeable that the injury distribution on the body regions - the injury pattern - shows some essential differences between the belt test subjects and the air bag test subjects.

Almost regularly occurred abdominal injuries in the belt group, reaching of small abdominal abrasions up to liver rupture of AIS 5; in the air bag group, in no case, injuries of the abdominal organs could be determined. In relation to side impact and rollover accidents, the use of a lap belt is frequently recommended in addition to the air bag. In such a combination of the restraint systems, similar abdominal injuries can be expected to occur. On the other hand, in the air bag group two times occurred severe injuries of the legs (AIS 3), which was not observed in the 3-point belt group.

These differences are not surprising if one considers that both used restraint systems especially load lower body parts with completely different force distributions: the lap belt of the 3-point restraint system loads the lower abdomen and the diagonal shoulder belt in its lower third the upper abdomen.

In the air bag-knee bar system the forces on the pelvis are transmitted over the knees and upper thighs.

If one considers the restraint function of both systems on the torso, the kinematical analysis of the head-neck region has already shown that in the air bag-knee bar system at the beginning of the rebound phase, a fast retroflexion of the head occurred; on the other hand, the 3-point belt protected occupant experiences a more extensive, but less fast forward bending of the head. Accordingly, in the air bag group lacerations of the frontal longitudinal ligament are more frequent in the transition of the cervical to the thoracic vertebral column with ventral lacerations and hemorrhages of the vertebral discs in this area; also tear drop fractures instead of ligamentum anterius. lacerations.

Lacerations of the dorsal ligamentous system, typical for the 3-point belt collective, especially of the ligamentum flavum combined with tear drop compression fractures were not observed in the air bag cases.

Injuries in the transition between thoracic- and lumbar vertebral column are found in both collectives; in the belt cases a bending load, similar as at the neck-thoracic transition; in the air bag cases an extension load was experienced. While the belt cases generally showed smaller injuries of a repeatedly injured spinal column in this lower spinal column region; in the air bag cases, the injury main point of the spinal column was just so often in the lower spinal column part as at the transition of cervical spine to thoracic vertebral spine.

Of course, also differences of the injury pattern of the thorax are to be expected as the air bag presents a broad surface load while the belt produces a ribbon-type, narrow load causing rib series fractures in typical cases, as known; the disposal of these fractures correspond to the belt geometry at the thorax. On the other hand, in the air bag tests, if at all numerous ribs are broken, it came to an asymmetrical disposal of the rib fractures right and left parasternal and/or in the axillar lines.

It was also remarkable that out of the 10 investigated air bag - knee bar cases 5 of them showed no rib fractures, among them a 66-year old female and a 37-year old male. The greatest number of rib fractures was not found in the older age group but in a 34-year old test subject.

In the belt tests out of 32 cases the ribs remained uninjured in 7 cases, exclusively in test subjects below 24 years of age.

The evident narrow connection between age and number of rib fractures in the 3-point belt tests could not be confirmed in the air bag group.

As learned from the kinematical analysis, also when regarding the injury pattern one has the impression that the course of the air bag inflation and the deceleration of the torso shows a much higher scatter rate in the air bag group as known from the 3-point belt system.

COMPARISON OF 3-POINT BELT AND AIR BAG - KNEE BAR KINEMATICS

A comparison between movements of the 3-point belt and air bag-knee bar tests has been made.

It is evident from film analysis that by the 3-point belt tests the cadaver wraps around the diagonal belt and is rather well kept back by the belt in some of the tests. This is dependent of the shoulder belt geometry. The following are sequence photographs of the side view of a 3-point belt test (Fig. 3), without rotation of the shoulder; further two sequence photographs of air bag - knee bar system tests with different kinematics, especially of the head-neck system (Fig. 4, 5).

In the 3-point belt test, Fig. 3, the subject is translatory moving up about 50 ms after the crash. The head starts to rotate 70 ms after the crash and reaches the maximum bending angle of 135 degrees at 120 ms after the crash. The rotation point is the transition of the cervical to the thoracic vertebral column. The shoulder reaches the maximum displacement already 80 ms after the crash; the rebound phase starts at this time period. Now a opposite-movement between shoulder and head exists, which is effective as a high rotation acceleration of the head - neck system in forward direction. About half of the mentioned rotation of 135 degrees occurred in a time of 40 ms. The rebound phase of the head starts 120 ms after the crash.*

The position of the test subject during the rebound phase can be found in Fig. 3. The head reaches at the start position about 220 ms after the crash.

Fig. 4 shows the sequence photographs of an air bag - knee bar test. The test subject was a 26-year old male, body mass 64 kg, body length 172 cm and sitting height 94 cm. Twenty-one ms after the crash the bag starts to inflate; 50 ms after the crash there is a first head contact with the air bag. The head deforms

*The kinematic with a preloaded 3-point belt is, however, more advantageous.

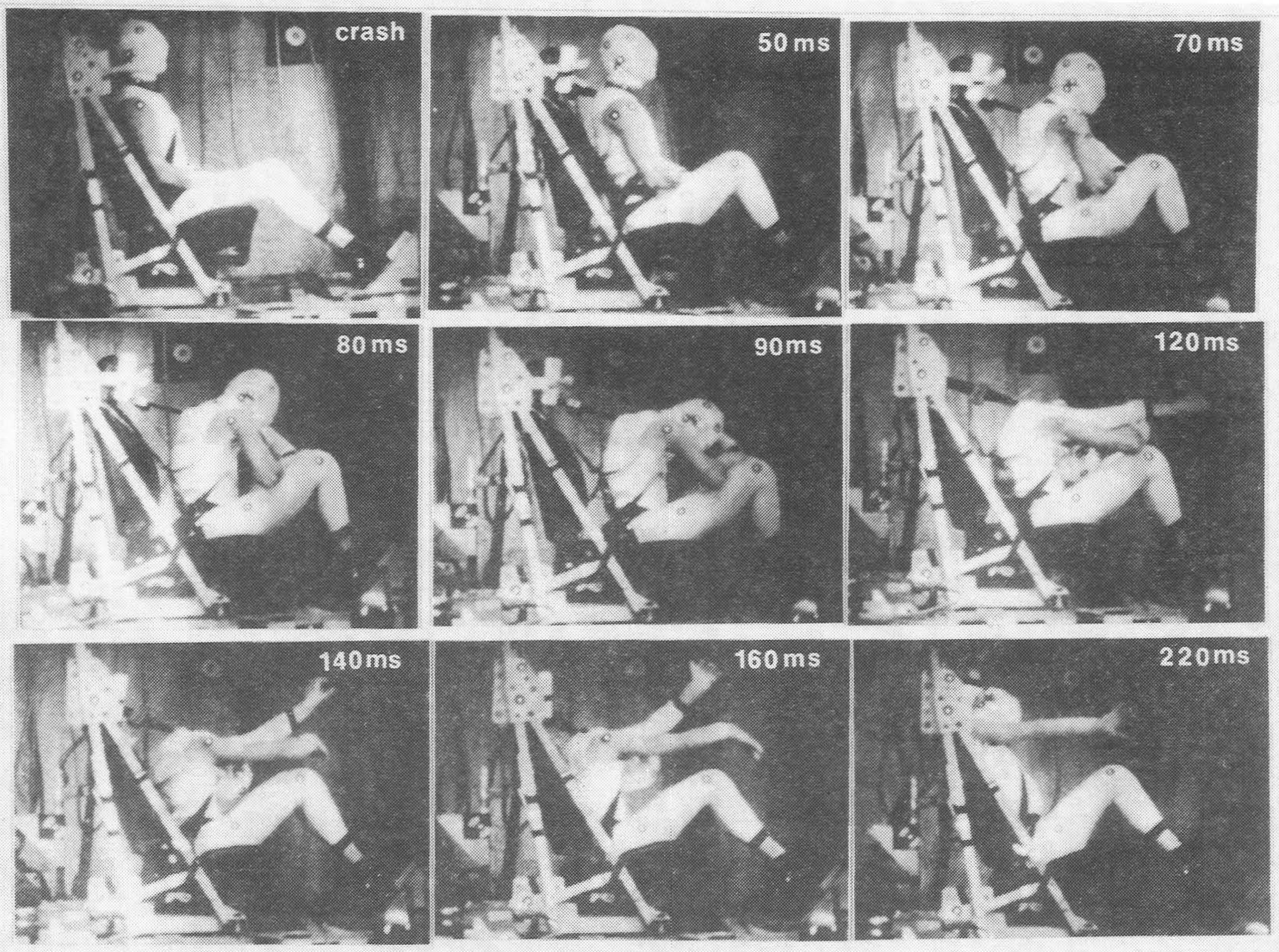

Fig. 3: Sequence photographs from high-speed movie during the crash. Restraint system: 3-point belt, testsubject: male, 29 years, 69 kg, 175 cm, NRF: 4, AIS thorax 2, AIS abd. 2, AIS vert. col. 1.

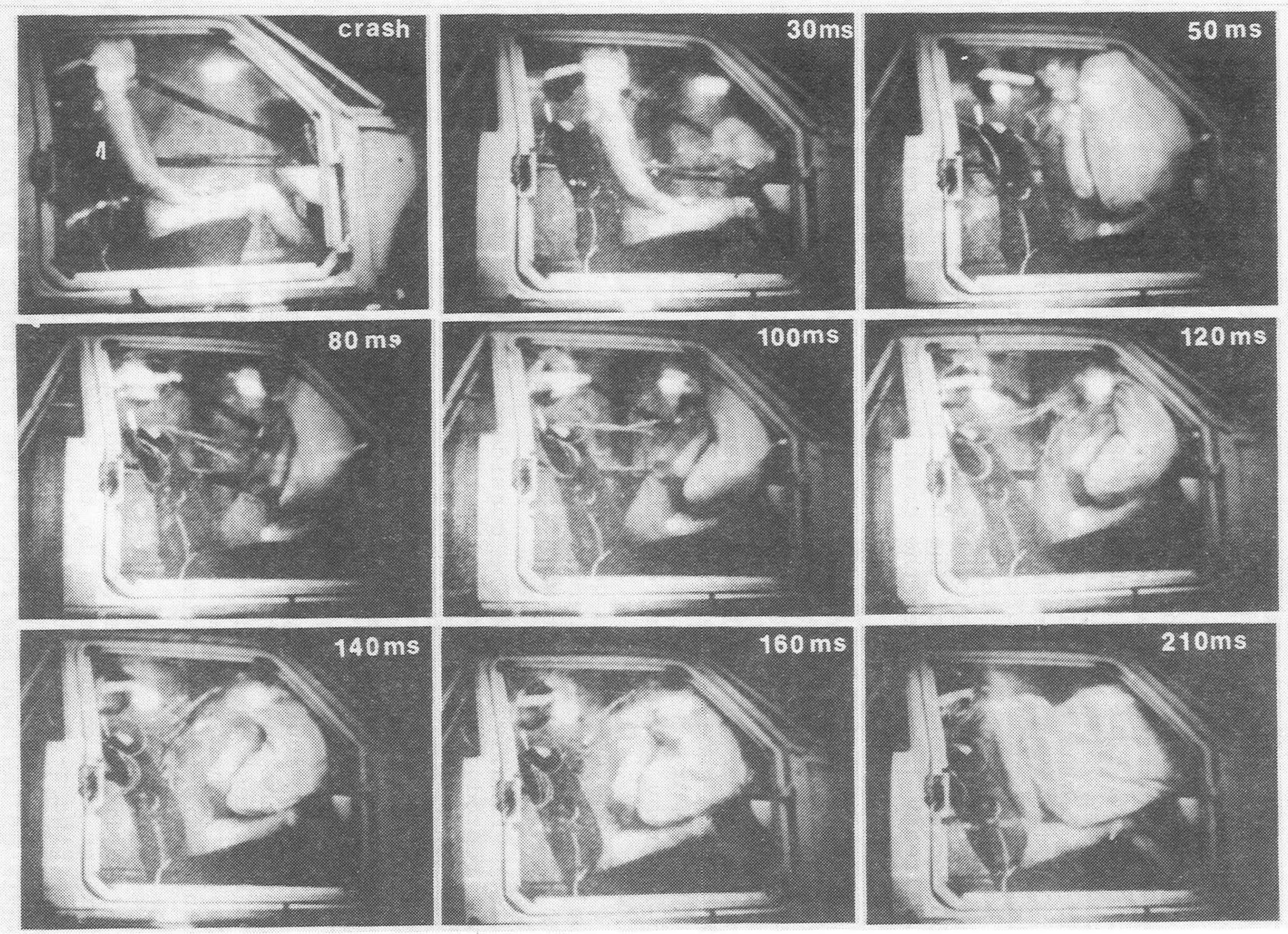

Fig. 4: Sequence photographs from high-speed movie during the crash. Restraint system: air bag - knee bar, testsubject: male, 26 years, 64 kg, 172 cm, NRF: 0, AIS head 0, AIS thorax 0, AIS vert. col. 0, AIS extrem. 0.

the bag, at the same time the cervical spine - head system moves forward. In this bended position the rebound phase begins. The shoulder reaches the start position about 210 ms after the crash; the head remains in a bended position until the conclusion of the rebound phase.

Fig. 5 contains the sequence photographs of a further air bag-knee bar system, which considerably differs from the above mentioned test. This test subject was also a male, 65 years of age, body mass 73 kg, body length 178 cm and sitting height 95 cm. The air bag begins to inflate already 12 ms after the crash; already 40 ms after the crash there is a first head contact with the air bag. About 90 ms after the crash starts the rebound phase and a backward bending of the head. About 120 ms after the crash a maximum backward bending of the head of 60 degrees is reached. This 60 degrees rotation of the head is done in a time period of 30 ms. Already 150 ms after the crash torso and head return to its starting position.

Looking for an explanation for these remarkable differences in the kinematic of the cervical column - head system of the above mentioned air bag-knee bar systems, the anthropometry of the test subjects has to be examined. The body length and the sitting height are very close together, however, in the body mass exists a difference of 9 kg. Surprisingly, in the thinner test subject a deeper pressing upon the air bag of the head was observed, whereby a stronger forward bending of the head came out.

Another reason causing the differences in the kinematic could also be the respective inflating times of the air bag and the first head contact with the bag.

Finally, it can be considered that it is not possible to exact reproducably control the removing of the gas filling of the air bag; therefore the kinematic of the test subjects varies by a different pressure - time history.

COMPARISON OF THE ACCELERATION-TIME-HISTORIES OF THE HEAD IN BOTH SYSTEMS

In Figures 6a, b and c, the head acceleration-time-histories of the above mentioned tests are described. In the 3-point belt test the maximum of the head acceleration in z-direction is reached 90 ms after the crash beginning and amounts 78 g. In x-direction a maximum of 36 g is reached after about 110 ms.

If these peaks are related to the returning points for shoulder and head established in the kinematical analysis, the maximum of the z-acceleration at the head corresponds to the turning point of the shoulder, however, occurs 10 ms later after the z-axis of the head has reached the horizontal by rotation.

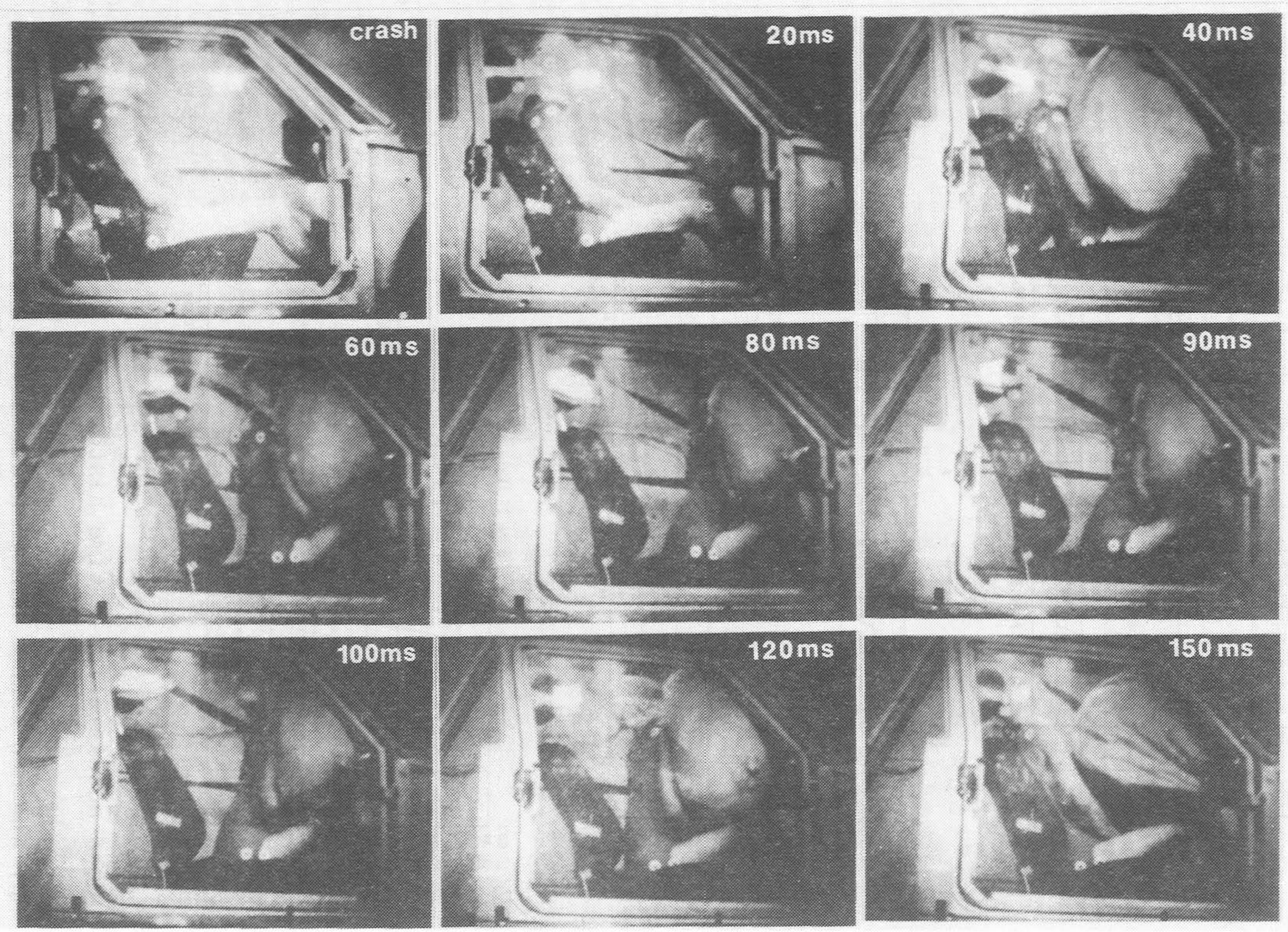

Fig. 5: Sequence photographs from high-speed movie during the crash. Restraint system: air bag - knee bar, testsubject: male, 65 years, 73 kg, 178 cm, NRF: 10, AIS head 0, AIS thorax 3, AIS vert. col. 4, AIS extrem. 0.

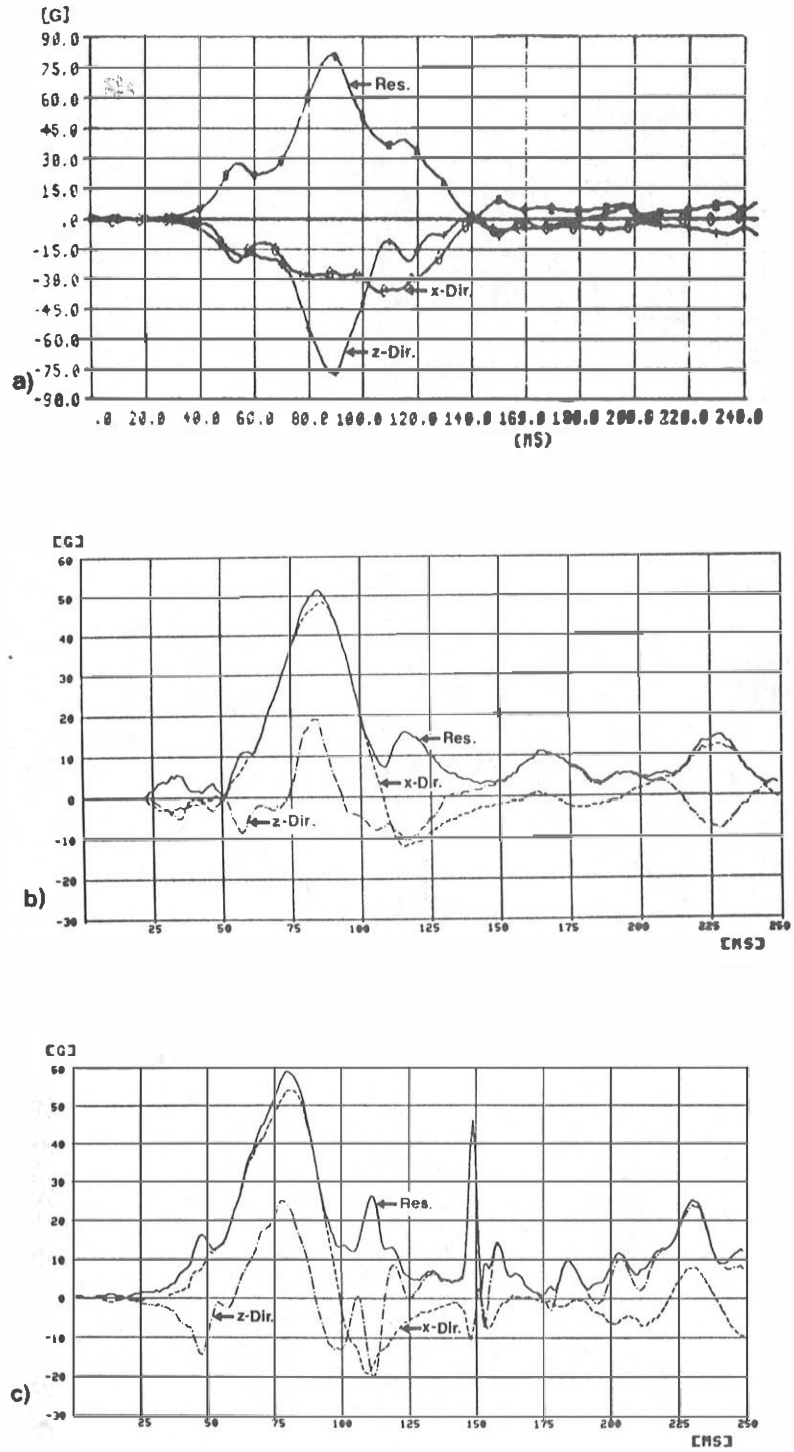

Fig. 6: Head acceleration - time histories

a) 3-point belt (Run No. 10 Table 1)
b) Air bag - knee bar (Run No. 3 Table 2)
c) Air bag - knee bar (Run No. 5 Table 2)

The maximum of the x-acceleration of the head coincides with the rebound start of the head.

The acceleration time curves 6b and c are identical in both tests. About 80 ms after the test the acceleration maximum for x-,z-direction of the head is reached. The maximum x-acceleration in both cases is about twice as high than the z-acceleration.

About 110 ms, acceleration peaks of the head in reverse direction are observed in both air bag tests.

In the test No. 5 (Table 2), the sequence photographs (Fig. 5) show that the backward movement of the head is the biggest shortly after the 2nd peak in opposite direction.

Following essential differences turned out when comparing the 3-point belt with the air bag-knee bar system:

1. The highest head accelerations were measured in z-direction in the 3-point belt system, and in x-direction in the air bag system.

2. In the air bag system a more violent acceleration is continued by a second smaller oppositely directed acceleration.

CONCLUSIONS

1. The mean values of the resultant head acceleration at the air bag-knee bar tests are lower than in the 3-point belt tests; the scatter, however, is higher.

2. The highest head accelerations are measured in the 3-point belt system in z-direction, in the air bag-knee bar system in x-direction.

3. There are existing fundamental differences in the kinematic between the two restraint systems.

4. The general trend showed that the injury severity of the air bag-knee bar tests are lower than the 3-point belt tests; the scatter is also higher here than in the air bag tests.

5. The injury pattern shows some essential differences between the 3-point belt system and the air bag-knee bar system.

6. The results of the present investigation cannot be transmitted to a comparison of the air bag system with a sensor controlled preloading 3-point belt system.

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