REACTIONS OF THE CERVICAL SPINE DURING FRONTAL IMPACTS OF BELT PROTECTED CADAVERS

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A. Introduction

No evidence does exist about the endangering of the cervical spine of injuries affected by safety belts.
According to BOHLIN (1967) the injury diminishing effect of safety belts in relation to the cervical spine is 100 percent for fatal and 20 percent for slight damages.
PATRICK et al (1974) seem to consider the injuries of the cervical spine not to be a major problem.
According to a new investigation made by DANNER (30 000 real accidents) cervical spine and thorax injuries of restrained persons are decreasing according to their seriousness, but are increasing in quantity.
HINZ (1971), CLEMENS and BUROW (1972), SCHMIDT et al (1974), KALLIERIS and SCHMIDT (1974), on the other hand were able to notice in many cases serious up to highly dangerous damages during controlled test conditions carried through with cadavers.
Tolerance criteria can only be found if the dynamical behavior and the multiple strain situations of the cervical vertebral column are more closely investigated.
During such investigations tests with volunteers, animals, cadavers, and dummies provide partial aspects in each case.

Own Investigations

Latest results and improved methods in order to record cervical vertebra column injuries are going to be described as follows. In a further chapter, by the aid of examples, optical evaluations will be discussed as a possibility of the investigation of reactions of the head - cervical vertebral column system.

Material and Method

Fifty-five cervical vertebral columns have been investigated which originated from simulated frontal crashes in passenger position.

Thereby the following test arrangements have been selected:

3-point-belt, automatic retractor (17% elongation at 1135 kp); sled velocity 50 km/h, 31 tests.

3-point-belt, automatic retractor, force limitor, preloading device (6% elongation at 1000 kp), sled velocity 65 km/h, 3 tests.

2-point belt, automatic retractor (17% elongation at 1135 kp), combined with a kneebar, sled velocity 50 km/h, 4 tests.

2-point-belt, automatic retractor, force limitor, preloading device (6% elongation at 1000 kp) combined with a kneebar, sled velocity 40 km/h, 3 tests; sled velocity 50 km/h, 12 tests; sled velocity 65 km/h, 2 tests.

The medium sled deceleration lay between 19 g and 25 g, the shoulder belt forces between 370 kp and 1020 kp. Not embalmed cadavers in the age range 12 to 79 years have been used whereby the laydays after death amounted from 20 to 90 hours. The subjects have been stored in a cold-storage chamber at 3°-5°C and have been brought at 15°-20°C prior to the test.

Thereby the rigor mortis was only treated in such a manner to obtain a seating position whereby the cervical spine remained unconcerned to a great extent. Prior to the test the rigor mortis of the neck has been checked and classified in four severity degrees. During the test the cadaver was dressed in elastical cloth for esthetical reasons (Fig. 1).

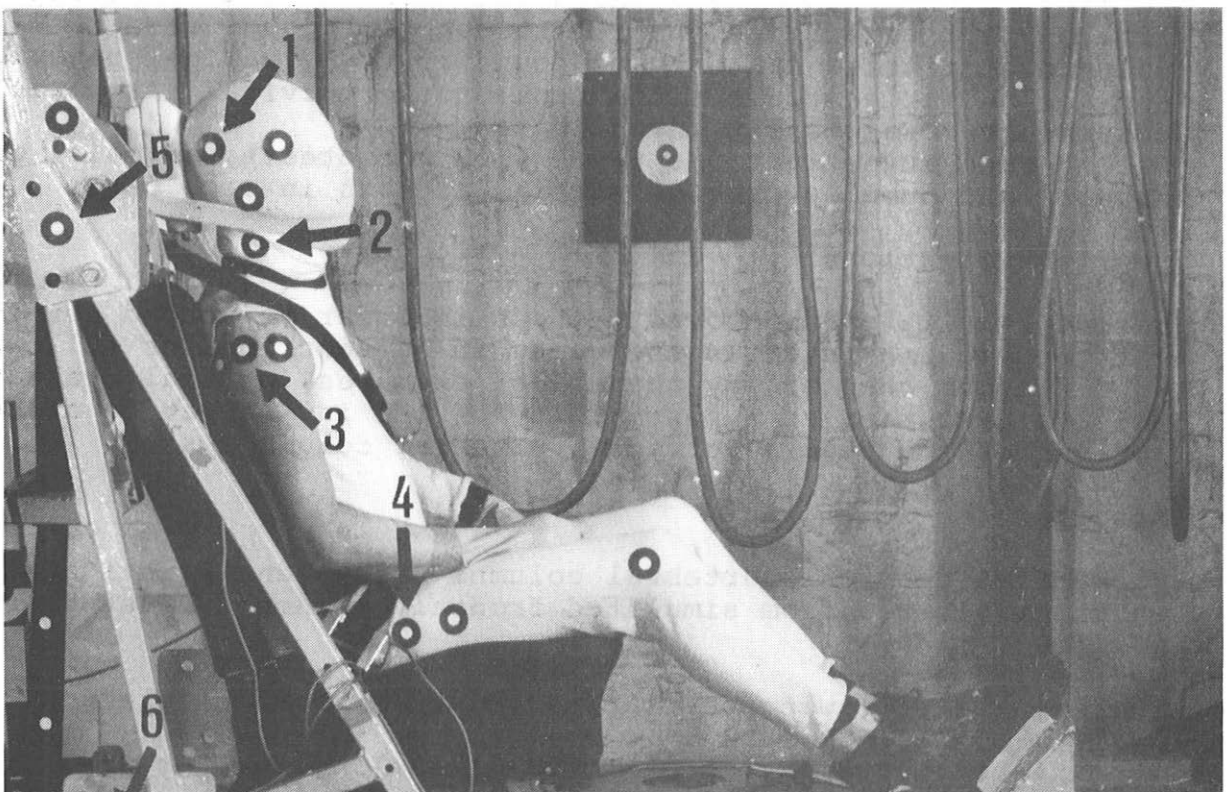

Fig. 1: Test subject with optical targets.

During the dissection the whole region, only with the skin prepared off, from the occiput to the 5th thoracic vertebra had been taken from the cadaver. The muscular system was prepared in layers, the cervical vertebral column was x-rayed with and without soft-tissue material.
In 21 cases the preparation has been subsequently macerated. In 34 cases the frozen muscle-free specimens were sawed up in three sectional planes.

Results

Because the injuries of the cervical vertebral column did not show differences in relation to the used belt systems in principle, a synopsis of the injuries of the single structures will be made in order to give an impression about the multiple kinds of injuries and strain possibilities (Fig. 2), findings of 34 frozen and sawed up specimens.

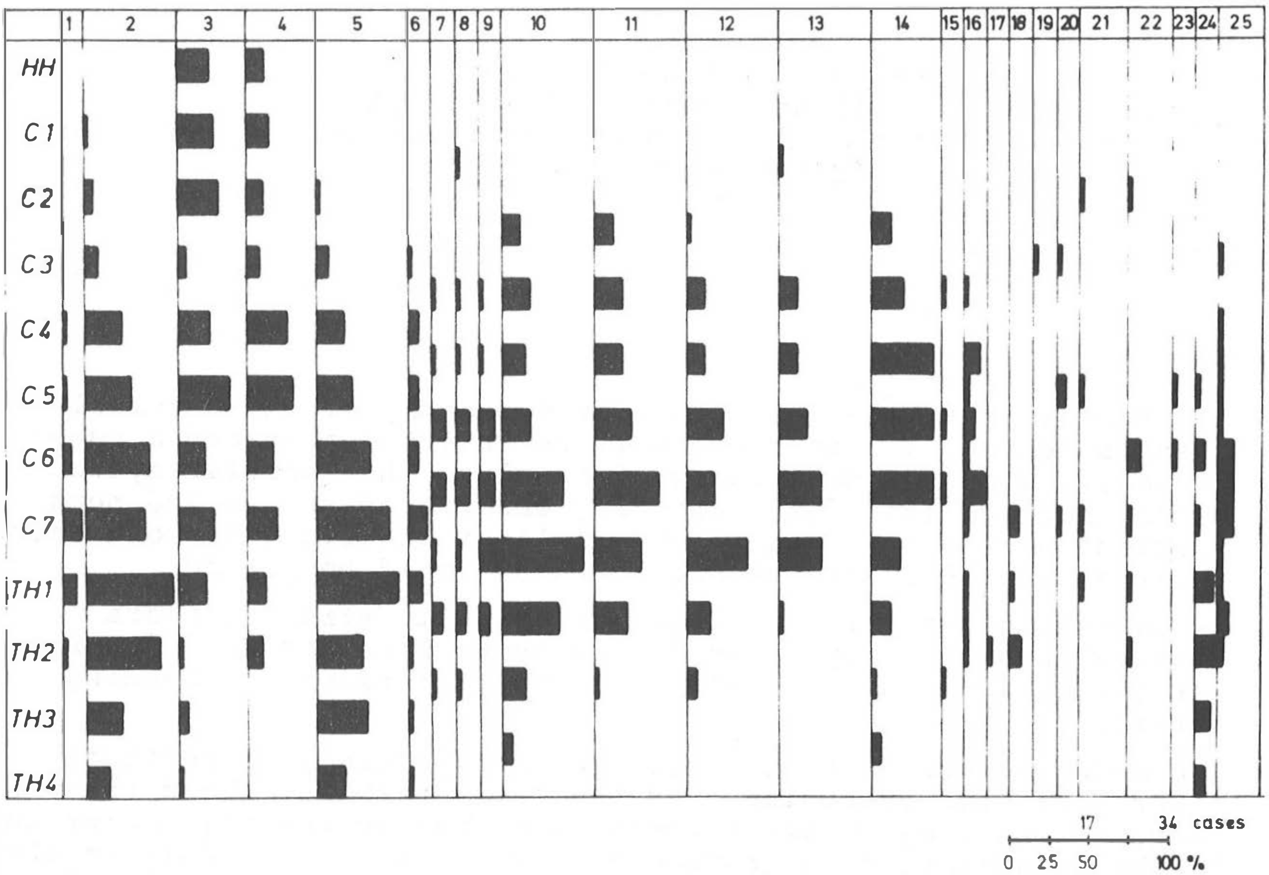

Fig. 2: Frequency and Localisation of Spinal Injuries (C 1 to Th 4; 34 specimens, prepared and sawed up).

No. 1 to 6: Muscular Hemorrhages and Lacerations

1-2-3 = superficial-medium-deep layer left
4-5-6 = deep-medium-superficial layer right

No. 7 to 9: Ruptures of Ligaments

7-8-9 = supraspinale-interspinale-flavum

No. 10 to 13: Hemorrhages of the Foramina Intervertebralia and the Vertebral Arc Joints

10-11 = for. intervert. right-left
12-13 = vertebral arc joints left-right

No. 14: Ruptures of Intervertebral Discs

No. 15 and 16: Ruptures of Longitudinal Ligaments

15-16 = lig. long. anterior-posterior

No. 17 to 24: Fractures

17-18 = processus transversus left-right
19-20 = vertebral arc fracture left-right
21-22 = arc and joint processus fracture left-right
23 = processus spinosus
24 = corpus vertebra

No. 25: Epidural Hemorrhage

Muscle Injuries

In order to simplify the complicated anatomy of the cervical spine somewhat, a difference will be only made between a superficial, medium and deep layer of muscles. The muscular system of the surface (all flat ventrally innervated spinal and neck muscles) only occasionally showed slight injuries. In most cases a direct impact in the secondary phase could be proved.

An explanation for this is because the main strain appears vertical respectively slightly transversal to its main fiber direction, the muscle itself broadens at tension and bending strain.

The medium layer (strong cross section, muscle with vertical fiber direction extending over several vertebras) shows the most frequent injuries in all severity degrees; in the main point the height localisation is grouped around C 6 to Th 2. Only in the medium and deep layer (the small, right next to the bones adjoining muscles as well as the short muscles between occiput and upper cervical vertebral column) showed muscular lacerations, those too occurred only in the transition of cervical vertebral column and thorax. In the region of the neck and head joints, the deep muscle injuries are at the most slight hemorrhages at both sides or at the left side only. The reason for this is that in the process of bending over when asymmetrically restrained in passenger position by the diagonal shoulder belt an increasing rotation of the head to the right side occurs, which to a great extent stops the anteflexion of the head - neck transition.

Injuries of the Ligamentous System and the Intervertebral Discs

Lacerations of the ligamenta supra- and interspinalia also occurred most frequently in the area of the cervico-thoracic transition whereby the muscular system was not involved in each single case, but regularly combined with fractures and/or in connection with lacerations of the intervertebral discs were found in connection with lacerations of the ligamenta flava. In almost all cases the intervertebral discs were dorsally lacerated The 3rd, 4th, and 5th intervertebral disc was mostly concerned, in about half the cases the posterior longitudinal ligament was involved. Series or multiple ruptures occurred more frequently than single lacerations, adjacent accompaying bony injuries have been noticed only with subjects beyond 45 years.

Bony Injuries

Compression-dependent fractures in the area of the upper thoracic vertebral column occurred as infractures up to dislocated teardrop fractures of the anterior end plate. Beside this, multiple lacerations of the processus spinosus occurred mostly at the lower cervical spine, also some fractures of vertebral arcs with or without the involvement of joint processus; however, no isolated fractures of the joint processus were noticed. In nine cases there was a fracture of the right 7th transverse processus which could be referred to a direct compression caused by the shoulder belt.

Injuries of the Vertebral Joints, the Foramina Intervertebralia and the Canalis Vertebralis

Besides of muscular injuries hemorrhages in the vertebral joints and in the foramina intervertebralia were the most frequent finding occurring mostly at the lower cervical level. An important extent of localized hemorrhages in the canalis vertebralis were altogether seldom. In this place it should be indicated that the findings of nervous tissue injuries pathoanatomical are very unsatisfactory (ERDMANN 1972).

Grades of Injuries

When classifying postmortal injuries we thought it convenient to assume as working hypothesis that not embalmed cadavers shortly after death can be equated with living persons at real accidents.

This appears to be true only for lesions of bones and ligaments (ROBERTS and LISSNER 1964, GREENBERG et al 1968). With the ever more increasing detailed analyses of real accidents the question of the transferability in regard to the behavior of cadaver tissues without blood pressure may be answered by comparison in the future. We have tried to transfer the up to now most comprehensive defined AIS scale on patho-anatomical findings about cadavers. The AIS scale and CRIS scale, however, is oriented according to clinical points of view.

We have tried to interpret them in a patho-anatomical classification:

Severity Degree:

I: Minor and moderate muscular hemorrhages mostly in form of small stripes without considerable distorsion of joints, indicating that cervical strain has occurred according to "whiplash without anatomical or radiological evidence".

II: Considerably muscular hemorrhages and ruptures, hemorrhages and ligamental dehiscences, hemorrhages of the vertebral arc joints and foramina intervertebralia not continued into the canalis vertebralis, isolated small ruptures of vertebral discs, isolated fractures of spinosus or transversus processus.

III: Fractures of vertebral arcs combined with lacerations of the dorsal ligamentous system, compression fractures, severe ruptures of intervertebral discs combined with lacerations of the ligamentum longitudinale posterious, which means a considerable reinforced opening or transversal displacement.

IV: Complete segmental disengagement, deniscent ruptures of vertebral discs combined with compression fractures or fractures of end plates. Considerable displacements of great bone fragments, beside the multiple combinations of severity degree III.

As distinguished from the results of CLEMENS and BUROW (1972), we never observed injuries which could be classified as primarily fatal from the patho-anatomical findings (higher degrees of the AIS).

With regard to the above mentioned investigations of real accidents modesty seems to be suited in the diagnosis of primarily fatal injuries produced post mortal.

The single test arrangements or impact velocities seemed to have a lesser effect on the severity degree of the cervical spine than the age (Fig. 3). Due to the small amount of tests, varying test arrangements, in this case, have not been taken into account.

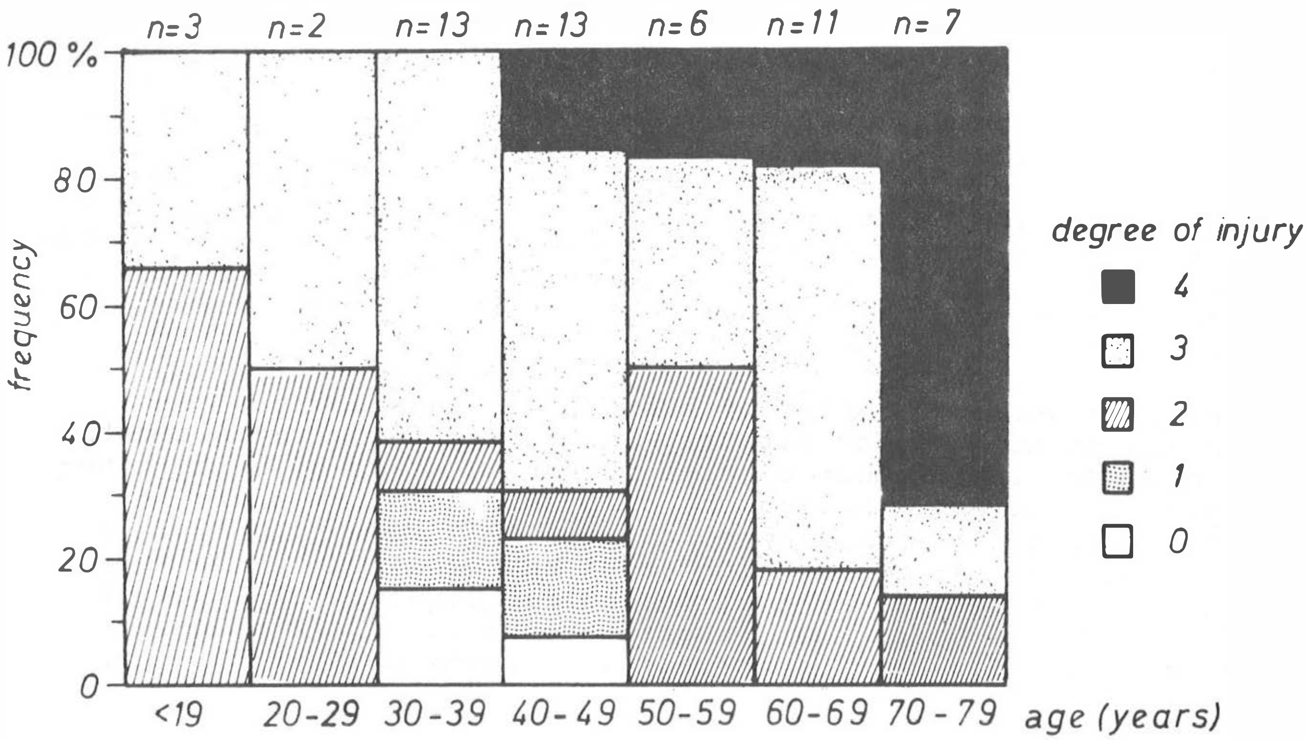

Fig. 3: Dispersion of the Injury Degrees of the Respective Age Groups Expressed in Percentage

B. Method of Determination of the Cervical Spine - Strain at Simulated Frontal Impact

An exact strain measuring of a cervical vertebral column during a test could result from a direct mounting of miniature accelerometers (linear acceleration, angle acceleration) or strain devices (rear, lateral, respectively in various levels) (BEGEMAN et al 1973).

Thereby the stability of those measuring elements has to be guaranteed. However, the mounting could not take place without an essentially preparation-dependent desintegration of the soft tissues surrounding the bony structures, and even the firmness of the small bony components be more or less impaired.

The comparison of accelerations and forces above and below the area to be investigated offers a second possibility as described and performed by MERTZ and PATRICK (1971). This strain determination which is composed of direct measurings and indirect calculations has the advantage of not influencing the firmness and kind of reaction of the cervical spine at all; the result, however, can at the most be an overall tolerance of all structures connected with the neck without a differentiation of its most infirm limbs.

The high-speed cinematographical evaluation offers a further possibility. It, up to now, was often applied during impactor tests (KROELL et al 1974) or also to check directly measured procedures at simulated frontal collisions (EWING et al 1968, 1969; HENDLER et al 1974). Here too, no influence is taken in regard of the system to be investigated. The principle is the optical pursuit of single marking points, installed on the body surface, in dependence on the time. Here too, an essential prerequisite is the relative stability of the optical targets which at least should not be greater than the common error rate of optical evaluations in general.

The displaceability problem of surface markings and the destruction of tissue when directly installing measuring elements can be eluded in the most elegant manner by means of x-ray cinematography. Hereby, the regions of possible injuries are visible during the whole impact phase. X-ray contrast illustrations of the vessels give information about the behavior of the soft tissues; the moment and the chronological sequence of injuries become evident. Up to now, investigations of this kind have been predominantly carried through with animals (SHATSKY et al 1974).

Own Investigations

At the installation in Heidelberg the strain of the cervical spine can be investigated by a laterally mounted high-frequency camera at 90° respectively by optical evaluation of the impact phases of the entire test at a framing rate of 1000/sec. The moment of the crash is marked by flash-light, the time is recorded by a time-scale on the film-edge as well as by a speed-constant time-indicator installed in the field of view of the camera.

The displacement plots of the targets which are installed on the cadaver to be observed in relation to each other and in relation to the points 5 and 6, those are firmly installed on the sled, are shown in figure 1. Comparisons of the cadaver's targets among one another serve for the angle determination. Of interest is thereby the angle between head and upper cervical spine (point 1 and 2), the angle between head and the entire neck (point 1 and 3) and the flexion at the transition of the cervical spine and the thorax.

The high-speed film, by means of a mirror, has been projected through a motion analyzer on a sensor field (flat plate). A free movable sensor provided with a line cross and press keys serves for the localization of the targets on the sensor field. Out of the electronical signals of the sensor and the sensor field the momentary position of the sensor in relation to a prior determined free eligible reference-point is investigated. The coordinate values resulting from each single target are simultaneously printed down by telewriter and punched on a perforated tape. By using a suitable computer program which contains corresponding mathematical filter functions, displacement plots, angle and angle velocities (as well as angle accelerations) of the provided points on the subject have been calculated by means of a Hewlett Packard 9810 A calculator. The curves have been recorded by a 9862 A calculator plotter.

In order to understand the following curves some limited prerequisites have to be pointed out:

1. Prior to the impact the distance between each target is measured to the sagittal plane of the subject respectively the camera for the evaluation. It is supposed that the points are not leaving the parallel planes to this sagittal plane.

2. During the impact there is no shifting of the photographical targets on the skin.

3. Optical contortions were not taken into consideration by a central picture section with a diameter of 1 m.

Results

With the aid of 4 cases evaluated in this kind, the above mentioned considerations will be made evident. At first, it deals about the comparison of two 3-point-belt tests with impact velocities of 30 km/h and a medium sled deceleration of 19 g. The cadavers for the test were characterized as follows:

T 10: Age 34 years, Weight 53 kg, Height 179 cm.

T 11: Age 48 years, Weight 81 kg, Height 174 cm.

Following injuries have been found at the cervical spine of those subjects:

At T 10 moderate hemorrhages of the medium and deep muscle layers of the cervico-thoracic transition on both sides; minor

We want to thank the Fa. Daimler Benz AG, especially Prof. Dr. Reidelbach for his friendly support during the evaluation of the films which is very gratefully acknowledged.

muscular hemorrhages between occiput and upper cervical spine; hemorrhages on the right side of the foramina intervertebralia C6/C7 up to Th1/2, as well as a very thin blood layer in the canalis vertebralis at the same level. Injury degree: II.

At T 11 moderate muscle hemorrhages above the medium and the below cervical spine, similar the one at T 10; as well as hemorrhages of several foramina intervertebralia and vertebral joints with an additional laceration of the whole dorsal ligamentous system and incomplete disc rupture at C7/Th1 as well as laceration of all dorsal ligaments and complete laceration of the intervertebral disc between Th1/Th2. Injury degree: III.

At T 4 similar injuries as T 10. Injury degree: II.

At T 9 similar injuries as T 11. Injury degree: III.

Fig. 4 shows the displacement plots of both collision tests. The movement pattern for the head (P1) and upper cervical vertebra column (P2) is nearly the same. The maximum displacement

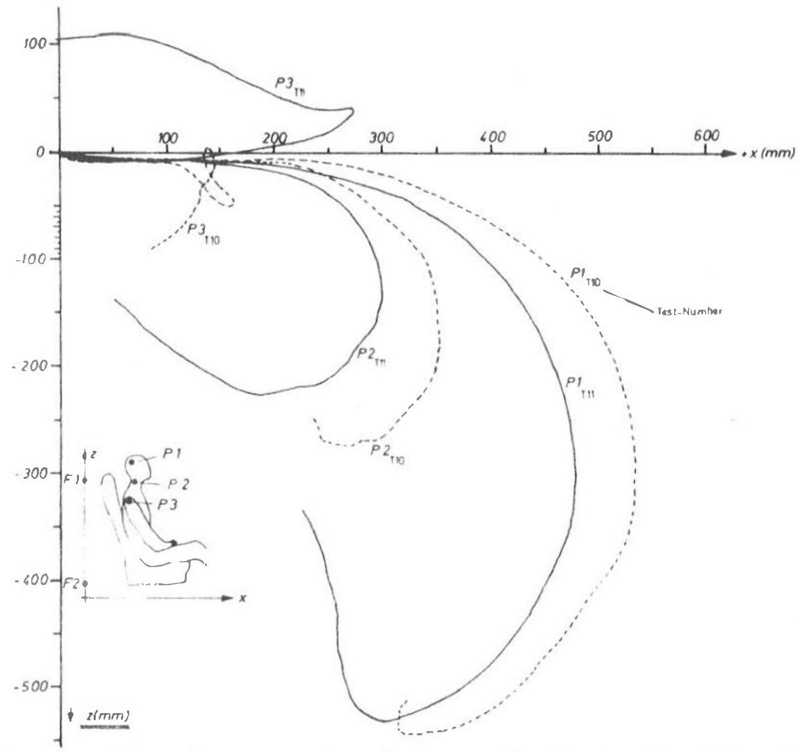

Fig. 4: Displacement plots of photographic targets, mounted on the head, neck, and shoulder of testnumber 10 and 11.

of both points is about 5 cm larger for T 10 and was reached within 92 ms after the impact; within 105 ms for T 11. A body seize exceeding 5 cm and a seating height exceeding even 8 cm of subject T 10 is conclusive for this maximum displacement, whereas the less body weight appearantly didn't influence the plots. However, shoulder-belt forces of 446 kp (T 10) respectively 539 kp (T 11) occurred proportionally to the body weight. They seem to have a lesser effect on the kinematical behavior of the cervical spine in relation to the path curve, but on the other hand a greater effect on the time history. A special difficulty appears at the path line of point 3 because of the interference with additional movements of the shoulder region after the shoulder-belt force has reached its maximum. For this reason we corrected the curves at the best possible way by means of auxiliary points and templates. Fig. 5 shows the angles of the axis P1/P2, P1/P3 and P2/P3 as against a sled-fixed axis in dependence on the time. It can be noticed that

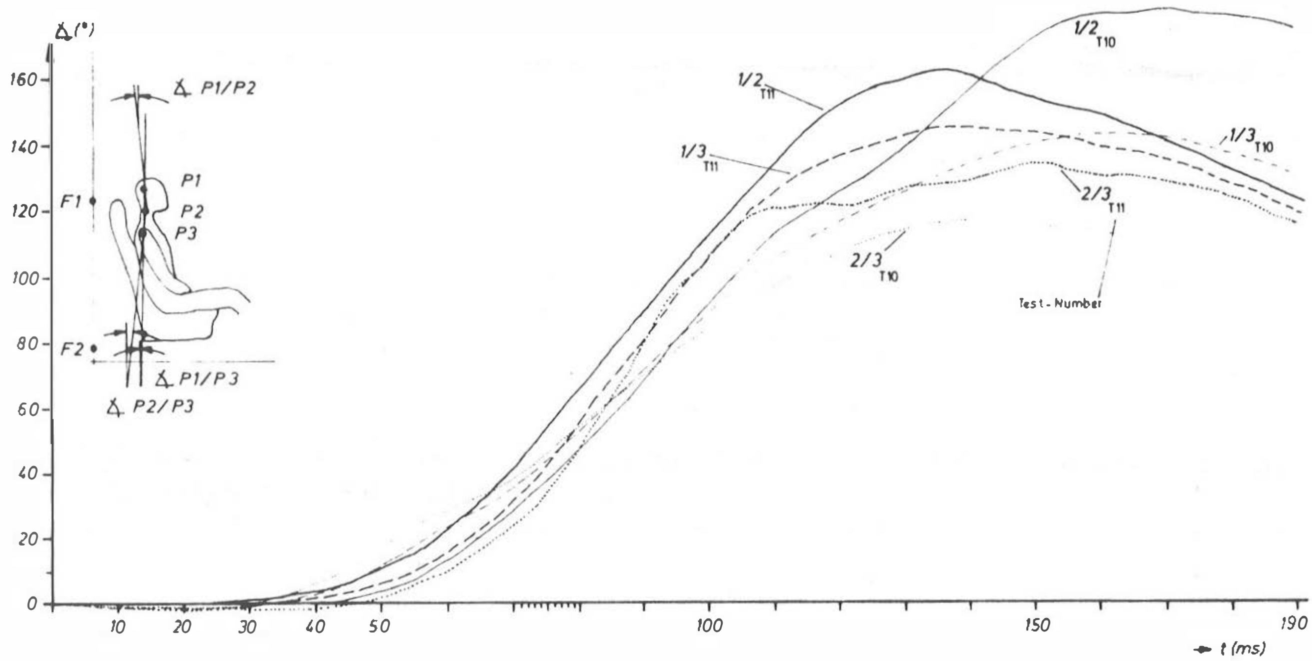

Fig. 5: Angle - Time History of the axes P1/P2, P1/P3 and P2/P3 as against the sled-fixed axis F1/F2 (Testnumber 10 and 11).

the optical targets up to about 40 ms are practically moving purely translatory. In the period of 45 ms up to 100 ms a nearly linear increase of the angles of all axes takes place; occurring parallel at both tests. The maximum flexion angles for all axes were reached for T 11 at approximately 130 ms, for T 10 at 140-160 ms. This means the ending of the primary impact phase at that time, the subsequent decrease of the angles corresponds with the secondary moving back. The corresponding angle velocities have been made evident in Fig. 6. During both tests the top velocity has been observed at nearly the same time, i.e. 90 ms after the impact. The maximum for T 11 (small displacement, low seating position, increased body weight, body height and shoulder-belt forces) however lies higher than the one for T 10.

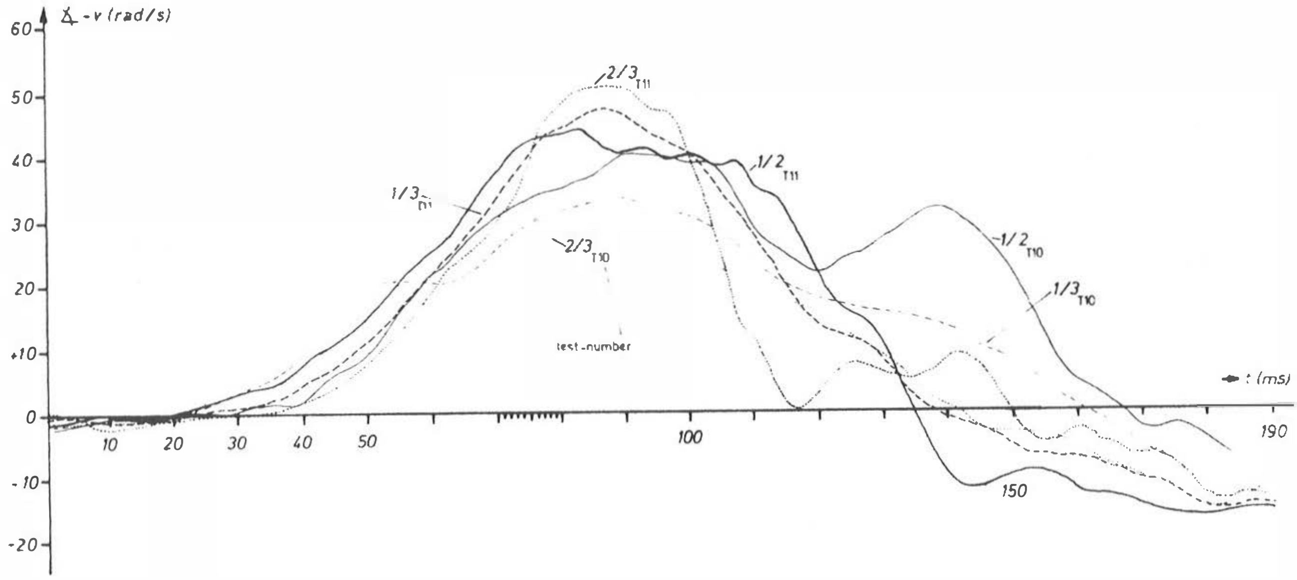

Fig. 6: Angular Velocity - Time History of the axes P1/P2, P1/P3 and P2/P3 as against the sled-fixed axis F1/F2 (Testnumber 10 and 11).

The following 2 tests are dealing with a 3-point belt test (T 9: ♀ age 24 years, weight 57 kg, height 161 cm) and a 2-point belt test (T 4: ♀ age 22 years, weight 57 kg, height 171 cm).

With the seating height of T 9 exceeding that of T 4 by 11 cm, a difference of the maximum displacement in x-direction results both for P1 and P2 of T 4, respectively 4,0 cm. In z-direction, the 3-point-belt tests show more than double displacement than that of the 2-point-belt test (Fig. 7).

Again, there is a purely translatory displacement of P1/P3 during the first 50 ms (Fig.8). An approximately linear increase of the angles up to 95 ms excluding the spinal axis (P2/P3) of T 9, whereas the maximum angular displacement occurs at about 110 ms after the impact. Again, all maxima of T 9 are above those of T 4.

At the angle velocities there is a chronological dissociation of the maximum heights. Yet again, the maxima of the test with the more serious injuries (T 9) even lie considerably beyond those of T 4 (Fig. 9).

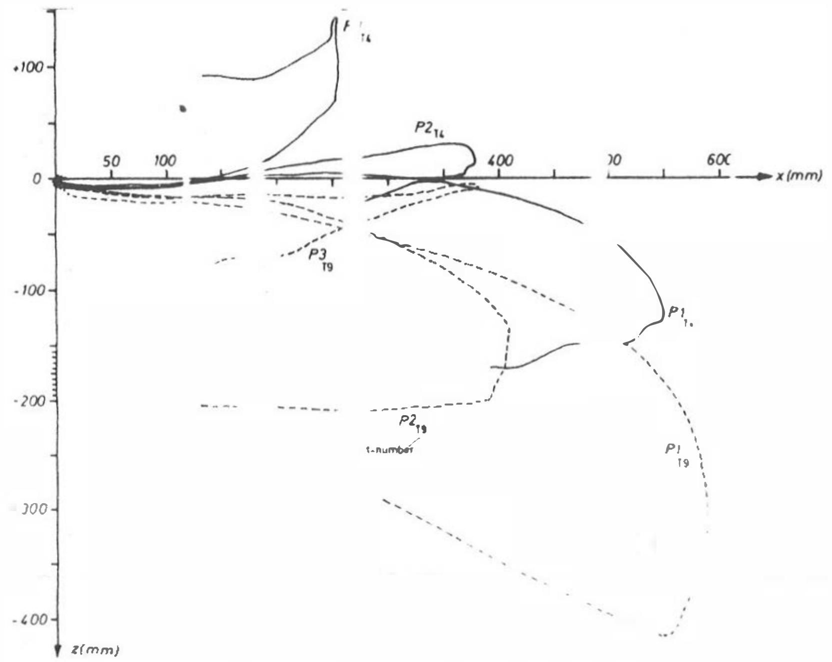

Fig. 7: Displacement plots of photographic targets, mounted on the head, neck, and shoulder of testnumber 4 and 9.

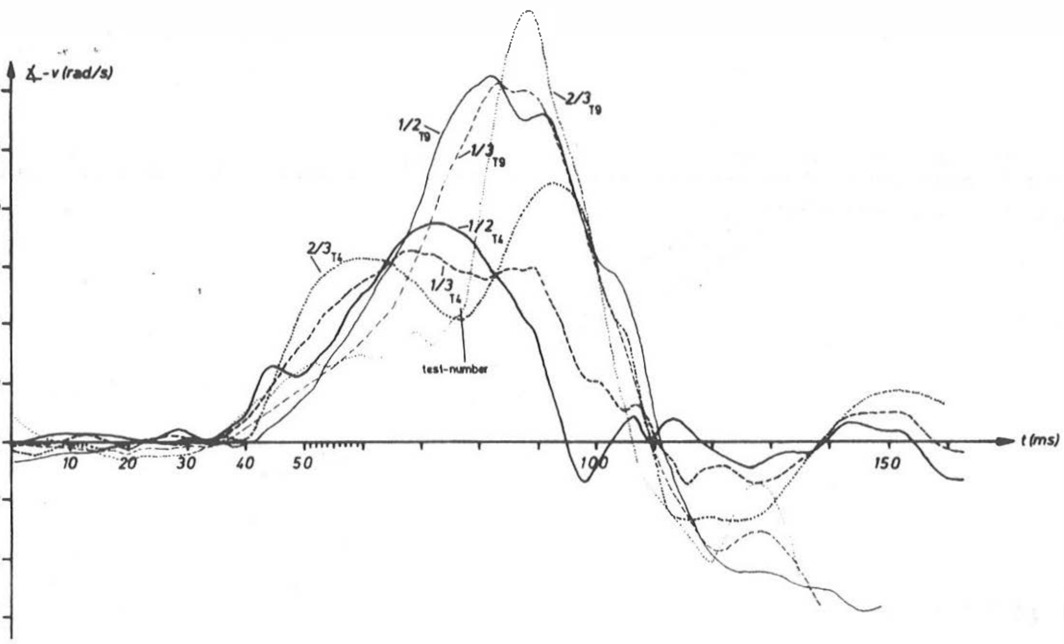

Fig. 8: Angle - Time History of the axes Pl/P2, Pl/P3 and P2/P3 as against the sled-fixed axis Fl/F2 (Testnumber 4 and 9).

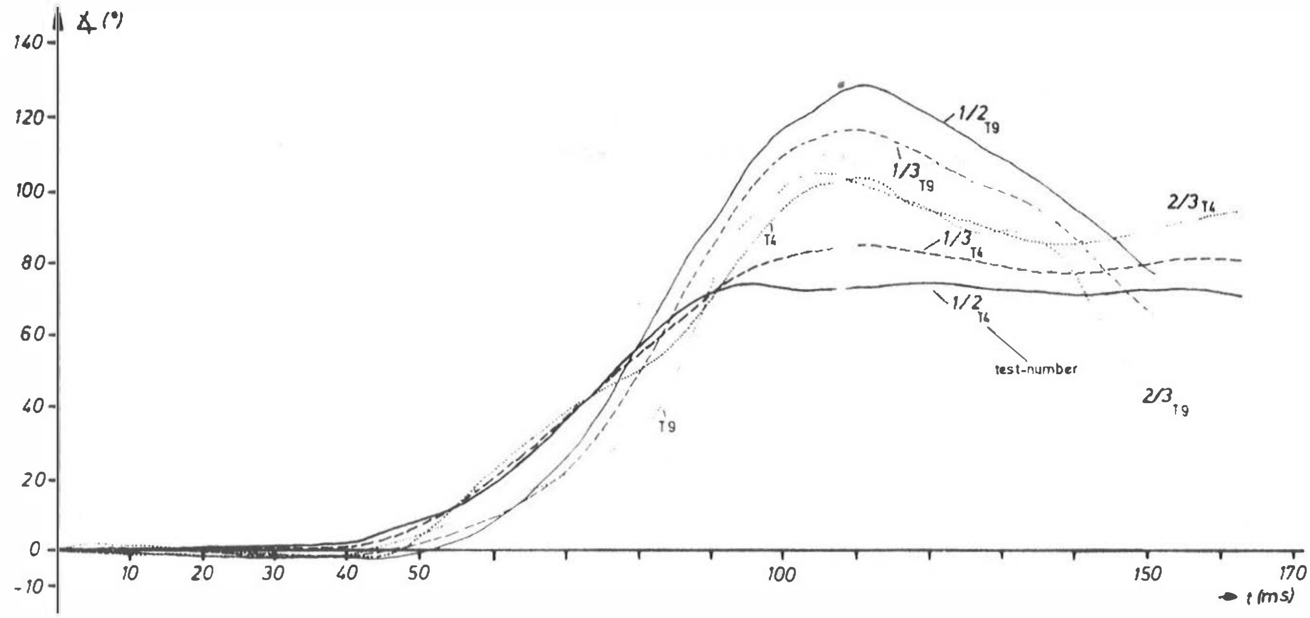

Fig. 9: Angular Velocity - Time History of the axes P1/P2, P1/P3 and P2/P3 as against the sled-fixed axis F1/F2 (Testnumber 4 and 9).

Fig. 10 shows the time history of the absolute flexion angle in the cervico-thoracic transition, the point of the greatest vulnerability of the cervical spine during the frontal impact.

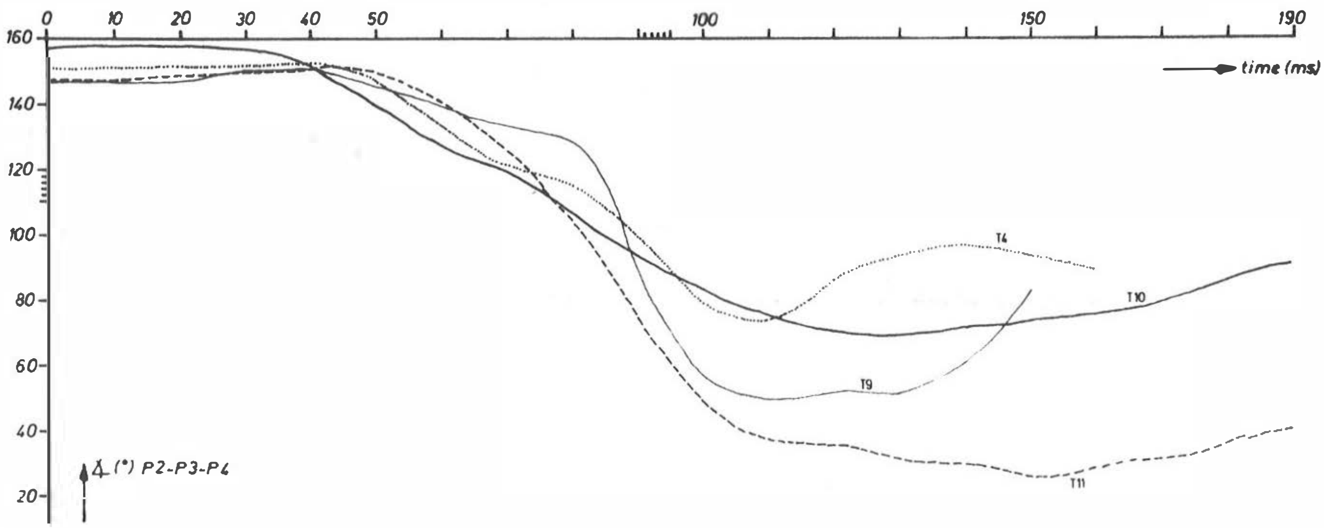

Fig. 10: Time - History of the angle P2-P3-P4 (Fig. 1) during the impact phase.

Again both tests showed a similar process; at the 2-point-kneebar test (T 4) however, the absolutely smallest maximum flexion angle has been reached.

During impact velocities of 40 km/h, the maximum flexion angles were attained at approximately the same time; whereas for T 9 a maximum flexion angle exists for a period of 35 ms; for T 4 the flexion angle is about by half shorter. The maximum angle alterations were observed at 90 - 100 ms. A preliminary calculation of the angle velocity showed the maximum value for T 9 at 98 rad/sec; T 11 at 54 rad/sec; T 4 at 26 rad/sec; T 10 at 23 rad/sec. This sequence corresponds with the severeness of the cervical spine injuries established in each case.

We hope that this conformity will be corroborated in our future tests. In this case the angle velocity of the cervico-thoracic transition could already represent a sufficient criteria for the strain in this region. The greater the optical resolution, the more exact could the cervical spine be separately observed in its single levels; in the ideal case by x-ray cinematography. Statements about the tolerance of each segment of the cervical spine could then be attained.

Not only the absolute tolerance limits but also the critical phase of the occupant cincematic, which causes the injuries, is of great interest for us. We shall try to investigate this critical phase by comparison of the maximum strain with the belt-induced movement of the test-body. Collision tests, in the kind carried through by us, can be used to purely imperical improve the restraint systems by alterations seeming meaningful to us.

Summary

1. Fifty-nine frontal barrier tests with human cadavers were carried through by the use of 3-point-standard belt with automatic retractor (34 cases); 3-point-belt with force limitor and preloading device (3 cases); 2-point-belt with kneebar (4 cases); and 2-point-belt, automatic retractor with force limitor and preloading device (18 cases). The impact speed was 30 km/h (2 tests), 40 km/h (5 tests), 50 km/h (47 tests), and 65 km/h (5 tests).

2. The observed injury degrees (patho-anatomical interpreted AIS scale) run up to 0 at 3 cases, to 1 at 4 cases, to 2 at 13 cases, to 3 at 29 cases, and to 4 at 10 cases. The severity degree was increasing according to the age of the subjects.

3. At 4 tests, displacement plots, angle-time-histories, angle-velocity-time-histories of the cranial-cervical and the cervical-thoracic axis have been investigated by optical evaluation of high-speed films. A greater displacement occurred

at a greater seating height, however, not at a greater body weight. During the first 40 ms (30 km/h impact velocity) respectively 50 ms (40 km/h impact velocity) a purely translatory movement of the cervical spine takes place. Maximum flexion angles have been attained at 30 km/h after 130 ms - 160 ms; at 40 km/h at 110 ms. The angle velocities were higher for more serious injured cervical spines than that for slightly injured ones.

4. Velocities of 98, 54, 26 and 23 rad/sec have been calculated for the angle of the cervico-thoracic transition.

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