Eur Spine J (1997) 6:366–375

ORIGINAL ARTICLE

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European Spine Society – The AcroMed Prize for Spinal Research 1997

Do "whiplash injuries" occur in low-speed rear impacts?

Received: 11 September 1997
Accepted: 16 September 1997

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Abstract A study was conducted to find out whether in a rear-impact motor vehicle accident, velocity changes in the impact vehicle of between 10 and 15 km/h can cause so-called "whiplash injuries". An assessment of the actual injury mechanism of such whiplash injuries and comparison of vehicle rear-end collisions with amusement park bumper car collisions was also carried out. The study was based on experimental biochemical, kinematic, and clinical analysis with volunteers. In Europe between DM 10 and 20 billion each year is paid out by insurance companies alone for whiplash injuries, although various studies show that the biodynamic stresses arising in the case of slight to moderate vehicle damage may not be high enough to cause such injuries. Most of these experimental studies with cadavers, dummies, and some with volunteers were perforemd with velocity changes below 10 km/h. About 65% of the insurance claims, however, take place in cases with velocity changes of up to 15 km/h. Fourteen male volunteers (aged 28–47 years; average 33.2 years) and five female volunteers (aged 26–37 years; average 32.8 years) participated in 17 vehicle rear-end collisions and 3 bumper car collisions. All cars were fitted with normal European bumper systems. Before, 1 day after and 4–5 weeks after each vehicle crash test and in two of the three bumper car crash tests a clinical examination, a computerized motion analysis, and an MRI examination with Gd-DTPA of the cervical spine of the test persons were performed. During each crash test, in which the test persons were completely screened-off visually and acoustically, the muscle tension of various neck muscles was recorded by surface eletromyography (EMG). The kinematic responses of the test persons and the forces occurring were measured by accelerometers. The kinematic analyses were performed with movement markers and a screening frequency of 700 Hz. To record the acceleration effects of the target vehicle and the bullet vehicle, vehicle accident data recorders were installed in both. The contact phase of the vehicle structures and the kinematics of the test persons were also recorded using high-speed cameras. The results showed that the range of velocity change (vehicle collisions) was 8.7–14.2 km/h (average 11.4 km/h) and the range of mean acceleration of the target vehicle was 2.1–3.6 g (average 2.7 g). The range of velocity change (bumper car collisions) was 8.3–10.6 km/h (average 9.9 km/h) and the range of mean acceleration of the target bumper car was 1.8–2.6 g (average 2.2 g). No injury signs were found at the physical examinations, computerized motion analyses, or at the MRI examinations. Only one of

the male volunteers suffered a reduction of rotation of the cervical spine to the left of 10° for 10 weeks. The kinematic analysis very clearly showed that the whiplash mechanism consists of translation/extension (high energy) of the cervical spine with consecutive flexion (low energy) of the cervical spine: hyperextension of the cervical spine during the vehicle crashes was not observed. All the tests showed that the EMG signal of the neck muscles starts before the head movement takes place. The stresses recorded in the vehicle collisions were in the same range as those recorded in the bumper car crashes. From the extent of the damage to the vehicles after a collision it is possible to determine the level of the velocity change. The study concluded that, the "limit of harmlessness" for stresses arising from rear-end impacts with regard to the velocity changes lies between 10 and 15 km/h. For everyday practice, photographs of the damage to cars involved in a rear-end impact are essential to determine this velocity change. The stress occurring in vehicle rear-end collisions can be compared to the stress in bumper car collisions.

Key words Whiplash · Clinical cervical examination · MRI · Spine injuries · Rear-end collision

Introduction

Though the passive safety features of automobiles have been continuously improved during the last few decades, the number of so-called "whiplash injuries" of the cervical spine has increased. An analysis of car accidents in Germany from 1990 reveals that in about 94% of rear-end collisions involving reported injuries, at least one passenger complained of a whiplash injury [3]. In 65% of all injury cases the velocity change due to collision (ΔV) was no higher than 15 km/h [2]. Interestingly, the incidence of reported whiplash injuries decreased in proportion to the extent of vehicle deformation. Whiplash injuries are most frequently encountered when only slight vehicle deformations (dents and scrapes) occur. In spite of this, between DM 10 and 20 billion are now paid out each year in Europe to car passengers claiming to have suffered such an injury to the cervical spine.

Given the slight stresses acting on passengers in accidents involving slight to moderate vehicle deformations, it is doubtful whether there is a risk of injury at all. In 1993, Meyer et al. [8, 9] demonstrated in an experimental crash-test study with volunteers that ΔV is a suitable technical parameter for describing the biomechanical stress acting on passengers following a rear-end collision. From the experiments, they concluded that a ΔV of up to about 10 km/h can cause no spinal damage. Meyer et al. [8, 9] also noted that bumper car collisions, which occur with varying directions of stress and body postures countless times everyday at amusement parks, involve high stresses to the cervical spine. ΔV values of up to 15 km/h were measured. In a review of the literature (a total of 242 experimental rear-end collisions with test persons), Szabo and Welcher [18] found a value similar to the one described by Meyer at el. [8, 9], namely 9 km/h. No significant injuries occurred at this velocity, and accordingly it was chosen as the standard value for further experimental studies. In a study providing an overview of the whiplash syndrome, Stovner [16] states that the correlation between the mechanism of injury and the symptoms has yet to be clearly demonstrated and that appropriate studies are urgently needed. We have addressed this need in our study. The purpose of this study was to expand on the study by Meyer et al. [8, 9] and conduct further crash tests with volunteers, which were then evaluated from a medical and biomechanical perspective. A major line of inquiry was to determine whether clinical or MRI signs of changes in the cervical spine can be demonstrated following a rear-end collision between two cars in a ΔV range from 10 to 15 km/h. Another goal was to determine the precise pattern of motion of the passenger's body in a rear-end collision, by means of biomechanical and kinematic analysis. This can provide information about the possible mechanism of injury. In addition to this, precise measurements of bumper car impacts were used in evaluating whether the biomechanical stress data of the passengers are comparable with those experienced in car accidents.

Materials and methods

Test subjects

Nineteen test subjects volunteered to participate after they were informed in detail about the study procedure and the risks it entailed (e.g., test subjects were told that it was not clear to what extent structural damage of the cervical spine could appear, especially with regard to soft tissues like musculature, nervous tissue, and intervertebral disks). Fourteen men between the ages of 28 and 47 years (average age 33.2 years) and five women between the ages of 26 and 37 years (average age 32.8 years) were available for 17 two-car rear-end collisions and for three bumper car collisions. One man participated in both a two-car collision and a bumper car collision.

Eighteen test subjects underwent extensive medical examinations 1–6 days before the collision (time 1), 1 day after the collision (time 2), and 4–5 weeks after the collision (time 3). One other test subject was only subjected to a bumper car test for purposes of biomechanical and kinematic analysis. First a patient history was obtained, followed by orthopedic examination of the cervical spine that included manual medicine techniques. The examination included evaluation of strength, sensation, and reflexes of the upper extremities. A computer-assisted ultrasound examination of the mobility of the cervical spine was performed using the CMS-50 unit manufactured by Zebris (although the exact significance of

this new technique of measurement of spinal mobility is not yet known). This examination measured rotation in maximum anteflexion and maximum retroflexion, in addition to measuring anteflexion and retroflexion, rotation in a neutral position, and lateral inclination.

An MRI study of the cervical spine was also obtained with each test subject (Magnetom Impact Expert, 1.0 T). A circular polarized spine phased array, as well as Magnevist (with the exception of the first three test subjects at time 1) were used. The following sequences were selected (field of view 500 mm):

1. T1-weighted, fast spin echo (FSE) 525/12/180°, sagittal plane, with and without Magnevist; slice thickness 4 mm, matrix 330 × 512, four acquisitions
2. T2-weighted, FSE 3243/112/180°, sagittal plane; slice thickness 4 mm, matrix 330 × 512, two acquisitions
3. T2-weighted, STIR 5244/60, coronal plane; slice thickness 4 mm, matrix 242 × 512, two acquisitions
4. T1-weighted, FSE 506/12/180°, coronal plane, with and without Magnevist; slice thickness 4 mm, matrix 330 × 512, four acquisitions
5. T2*-weighted, GE 480/22/25°, transverse plane; slice thickness 3 mm, matrix 160 × 256, five acquisitions

Two radiologists evaluated the MR images independently of one another according to the following criteria: appearance of the intervertebral disks, spinal cord, ligamenta flava, facet joints, and musculature, the position of the cervical spine and the axis of the dens, the atlantodental distance and atlanto-occipital distance. Conflicting evaluations were resolved by having the examiners jointly reevaluate the images in question.

Evaluation of the examinations at time 1 revealed that eight test subjects (i.e. nine collisions) had suffered previous cervical spinal symptoms prior the test. At the time of the test, all subjects were free of symptoms.

The ultrasound analysis of cervical spine motion showed changes in at least one direction of motion in every test subject prior to the tests.

The preliminary MRI studies revealed degenerative changes in seven test subjects (i.e., eight collisions). Protrusion of the intervertebral disks with slight compression of the epidural and subarachnoid space was seen in five test subjects. Protrusion completely compressing the epidural and subarachnoid space was seen in one test subject. This was the person involved in two tests. A degenerative anulus tear was found in another test subject (Fig. 1). Two test subjects experienced claustrophobic reactions that prevented completion of the MRI studies.

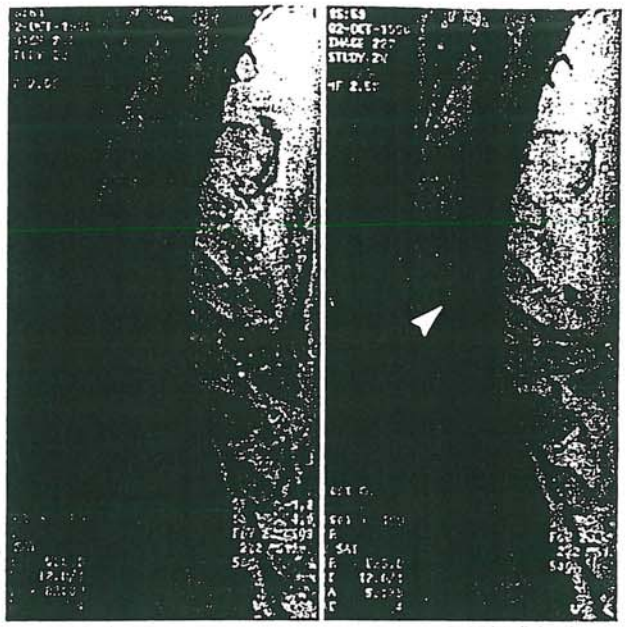

Fig. 1 Fast spin echo MR images of the cervical spine in the sagittal plane before the crash (FSE 525/12/180°). In this 30-year-old test subject, the *right-hand image* (enhanced with gadolinium) shows a circumscribed pattern of enhancement indicative of a degenerative tear in the posterior portion of the anulus fibrosus of vertebral segment C4–C5 *(arrow)*

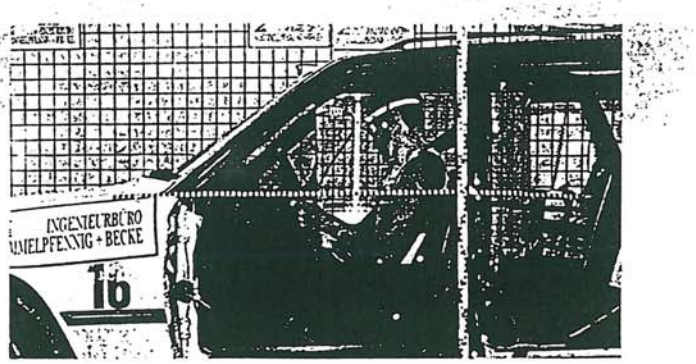

Fig. 2 Initial position of a male test subject immediately before a two-car collision. Note the blinds, the headset, and the leads connecting the test subject to biomechanical acceleration and electromyography (EMG) sensors

Test series

The safety of the test subjects was the highest priority throughout the experiments. Accordingly, collision velocities were calculated in advance so that the stress values could not exceed those that can occur in bumper car impacts [8, 9].

Anticipation by the test subjects was largely neutralized. Their vision was obscured by opaque eyeglasses and loud rock music was played on a Walkman (Fig. 2). In two test subjects, anticipation could not be excluded because the music was interrupted and the approaching vehicle could be heard. Activity of the neck muscles (sternocleidomastoideus, trapezius, and splenius capitis) was continuously recorded via surface electromyography (EMG). In two test subjects a complete EMG recording could not be achieved due to technical problems.

The movements of the test subjects were recorded with a high-speed camera (60 or 100 frames per second), a video camera (25 frames per second), and a recording unit for motion analysis. The two-dimensional motions were recorded with a Hammahatsu C1161 camera with a Nikon 35-mm small-image lens positioned perpendicular to the target vehicle. The respective motions of the vehicle, seat, headrest, and test subject were recorded using movement markers. These markers were made of reflective Scotch Lite foil, with a diameter of 10–20 mm. Using ten movement markers, the system screen frequency was 732 Hz. The data obtained in 12 of the 20 crashes were sufficient for a motion analysis to be made, although in 4 of these some markers were lost during the impact. In the remaining eight crashes a motion analysis was not possible because too many markers were lost. Accident data recorders manufactured by Mannesmann-Kienzle were installed in the target and bullet vehicles. This allowed recording of the longitudinal and transverse vehicle acceleration. Velocity was also measured by a photoelectric barrier (Alge-Sporttiming) immediately in front of the collision site. A computerized crash data acquisition system in the target vehicle (custom design by Ingenieurbüro Schimmelpfen-

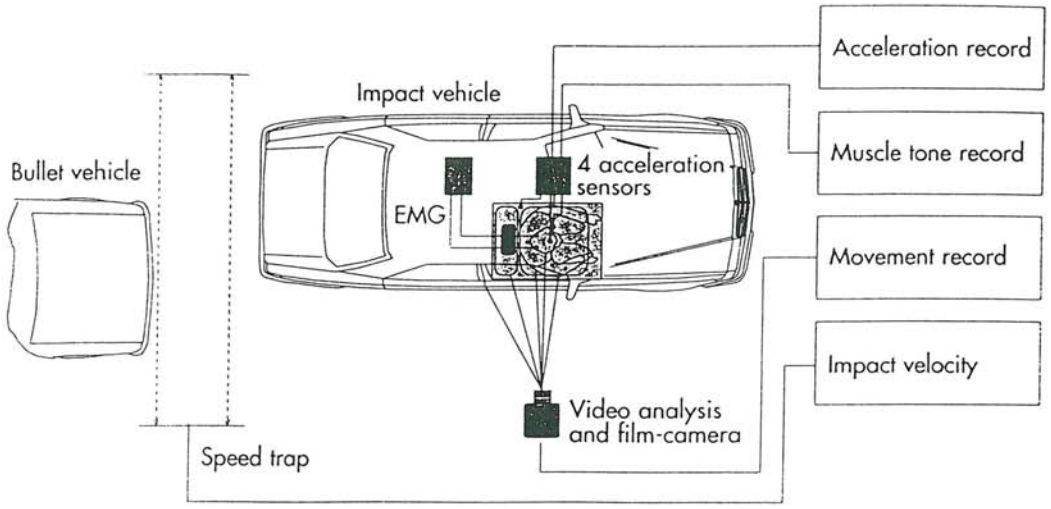

Fig. 3 Design of the experiment

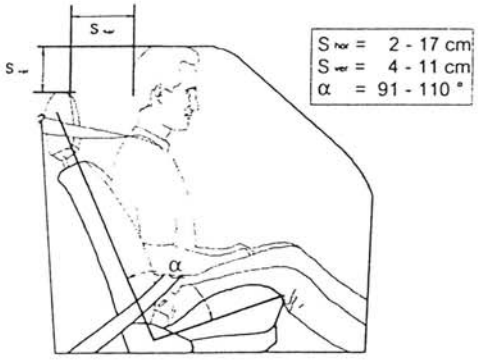

Fig. 4 Initial position in the car seat

nig und Becke) was used to record the longitudinal and vertical acceleration of the passenger compartments and the acceleration of the test subject's chest and head. Figure 3 provides an overview of the design of the complete experiment. All acceleration data were acquired simultaneously with the EMG data.

The sitting position of all test subjects in the vehicle and the seat adjustments were photographed a few minutes before the test with a tripod camera under defined conditions (distance, height, and angle). The precise position of the movement markers, the horizontal distance between the head and headrest, and the vertical distance between the top of the head and the top of the headrest were measured and recorded. The horizontal distance s_{hor} ranged from 2 to 17 cm and the vertical distance s_{ver} ranged between 4 and 11 cm. The angle of inclination between the surface of the seat and the backrest varied between 91° and 110° (Fig. 4).

The vehicles used (VW Golf II, Opel Kadett E sedan/station wagon, Opel Rekord E, and Daimler Benz W 124 sedan/station wagon) are common models equipped with standard European bumper systems. Since most rear-end collisions involve bullet vehicles whose front ends dip as a result of braking (nose diving), the front ends of 14 of the bullet vehicles in the tests were lowered. In all target cars the handbrakes were applied to simulate real accident situations in which people often apply their brakes during the impact.

Every vehicle was individually photographed prior to the experiments to document possible previous damage. Immediately after the respective tests, the condition of the vehicle was again documented under the same conditions (i.e., distance and angle of the photographs).

With respect to measurement engineering, the same experimental design was implemented for the three bumper car collisions.

Results

Time delay of the sensor signals

The time delay between the beginning of acceleration of the passenger compartment and the biomechanical signals from the chest and head together with the onset of the EMG signal, as a function of the velocity change due to collision for all two-car impacts is shown in Fig. 5. In this graph, the zero point is defined as the beginning of acceleration of the passenger compartment. Movement of the upper body (chest) begins on average approximately 48 ms after the beginning of acceleration of the passenger compartment, whereas a significant movement of the head is only detected about 90 ms after initial contact between the two vehicles. The detected neuromuscular reaction of the muscles of the back of the neck begins on average about 60 ms after the passenger compartment begins to accelerate and approximately 20 ms after the chest movement begins.

Motion analysis

Using the preliminary data of the biomechanical acceleration signals measured at the head and chest and the ten movement markers, we were able to divide passenger motion in a rear-end collision into one primary motion involving six constantly recurring phases (Fig. 6) and one secondary motion.

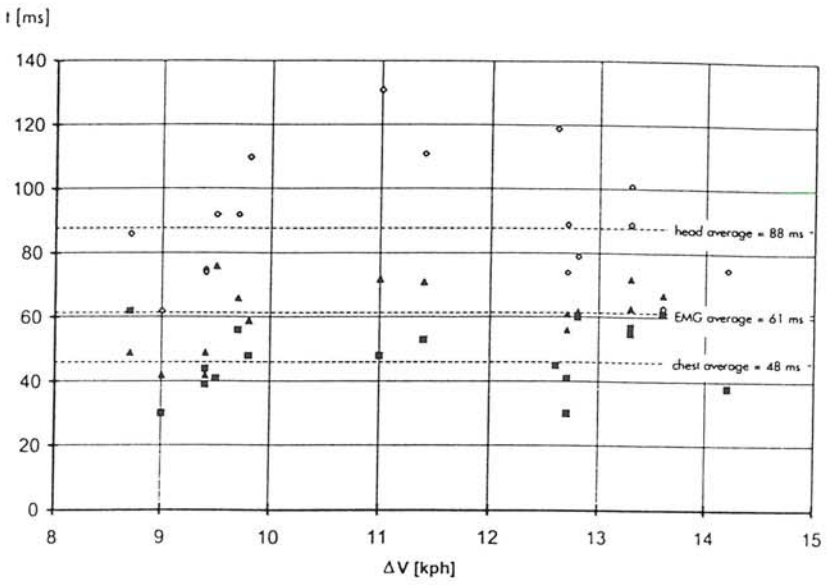

Fig. 5 Time delay between the beginning of acceleration of the passengers compartment and the biomechanical signals from the chest (■) and head (◇) together with the onset of the EMG signal (▲) over the velocity change due to collision

The primary motion
(from the rear, relative to the passenger compartment)

Phase 1: The passenger compartment and seat move toward the passenger's resting body. By definition, the beginning of this phase is identical to the beginning of the collision, i.e., the time of the initial contact between the two cars. During this phase, the lower seat upholstery of the backrest is deformed in the region corresponding to the passenger's pelvis.

Phase 2: This phase begins with the forward motion of the test subject's pelvis. The friction between the surface of the seat and the volunteer's thighs, and the frictional connection between the lumbar spine and the backrest, cause the passenger's lower body to move forward. This reduces the angles between the torso and the head, although the head and upper body are not yet in forward motion. This produces flexion in the cervical spine.

Phase 3: Onset of upper body motion (chest). Because the force transmitted by the frictional connection between the backrest and the passenger continues upward to the thoracic spine from below through the hip, pelvis, and lumbar spine, the chest begins to participate in the forward motion. The head remains at rest. This introduces a relative translational motion between the upper body and the head. Remarkably, at the onset of this shear stress, the passenger compartment and seat have already moved forward approximately 11 cm.

Phase 4: The force travelling upward through the frictional connection reaches the shoulder blades, forcing the passenger into extension. The passenger appears to rise up in the seat in what is known as "ramping". By this time, the seat and passenger compartment have already moved forward approximately 20 cm while the head still remains at rest.

Phase 5: This phase is characterized by the maximum angle of deformation of the backrest and the completion of passenger extension. The extension motion of the head has begun, i.e., the angle between the upper body and the head increases noticeably.

Phase 6: The maximum angle of extension is reached after the back of the head has come into contact with the headrest. The passenger is in full extension, and now every part of the body is involved in the forward motion of the seat and passenger compartment.

The secondary motion

The secondary motion occurs immediately after the six phases mentioned above. As the backrest resumes its shape, the passenger accelerates forward relative to it and is thrown forward against the seatbelt.

Relative angle and angular velocity

Motion analysis can determine the maximum angle and the maximum relative angular velocities (12 of 17 car collisions) between the upper body and the head in the extension motion. Figure 7 shows the resulting relative angle as a function of the horizontal distance between the back of the test subject's head and the headrest. This varied between slightly less than 10° and 47°. The average extension angle was 20°. The maximum relative angular velocities (Fig. 8) ranged between 200° per second and a

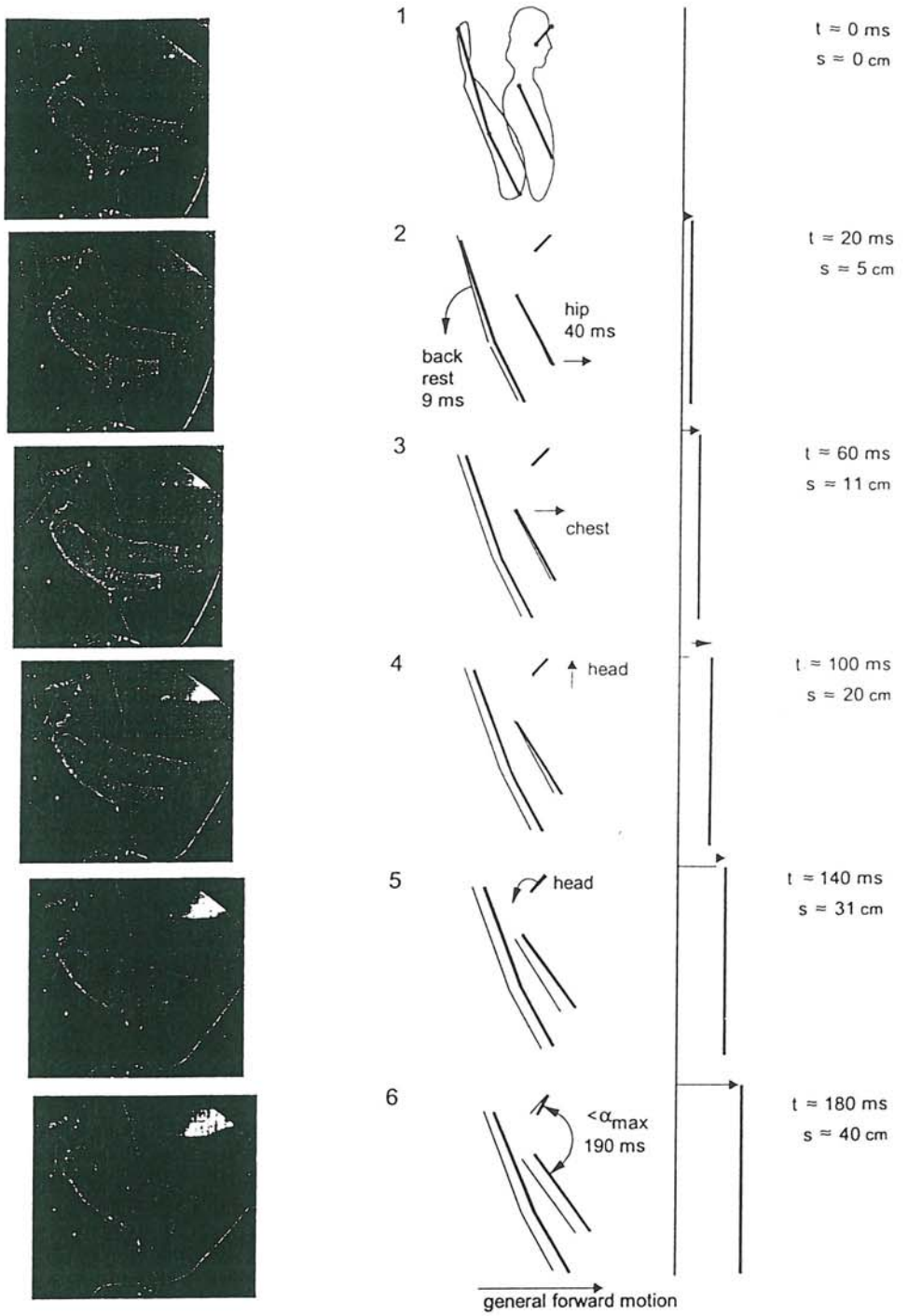

Fig. 6 Analysis of a primary motion with six constantly recurring motion phases. The images from the video camera are shown on the *left*. The movement markers are visible as bright spots on the seat and test person (forehead, center of gravity of the head, shoulder, and hip). As shown in the *top middle image*, these points were corrected together to allow separate tracking of the absolute motion of the seat, upper body, and head. In each of the consecutively numbered line diagrams, the current positions are shown with *solid lines* and the respective previous positions (approximately 40 ms previously) are shown with *dotted lines*. The times *t* and absolute distances *s* of the passenger compartment, relative to the time of initial contact of the vehicles and the rest position of the target vehicle respectively, are specified in the *right section* of the Figure. A description of the various phases is given in the text

maximum of slightly less than 1600° per second. The average angular velocity was 606° per second (12 of 17 car collisions).

The patterns of motion recorded in the three rear-end bumper car collisions are comparable in terms of the phases of motion discussed above. This applies particularly to the translational motion between the upper body and head, i.e., phase 3. The significant difference between the motions in the car and those in the bumper car is that a hyperextension motion was seen in the bumper car due to the lack of a headrest. In one test the resulting maximum relative angle between the upper body and head exceeded 80°. None of the results in the car crash tests even came close to achieving this angle. Hyperextension of the cervical spine and head was prevented in the car impacts by the headrest. Since the head can travel much farther

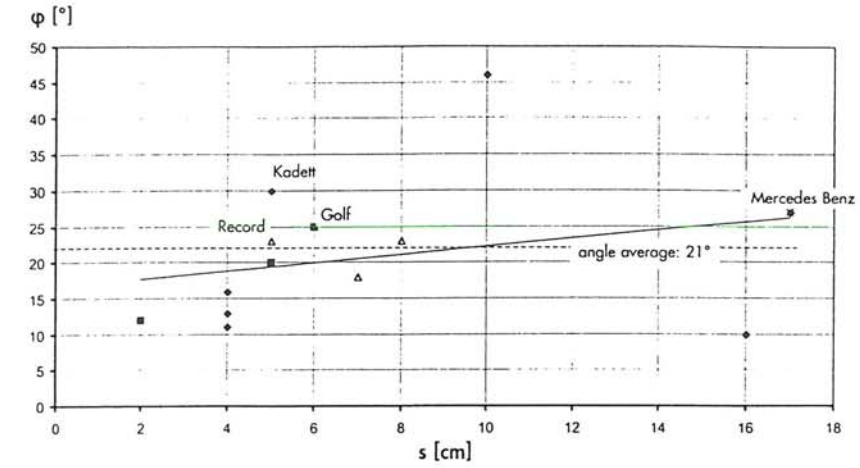

Fig. 7 Relative angle in relation to the distance from the headrest

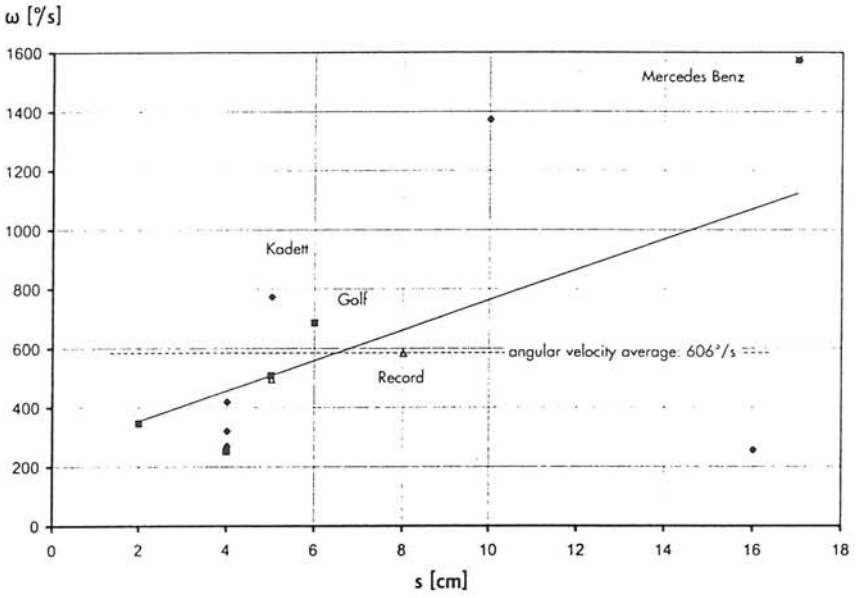

Fig. 8 Relative angular velocity in relation to the distance from the headrest

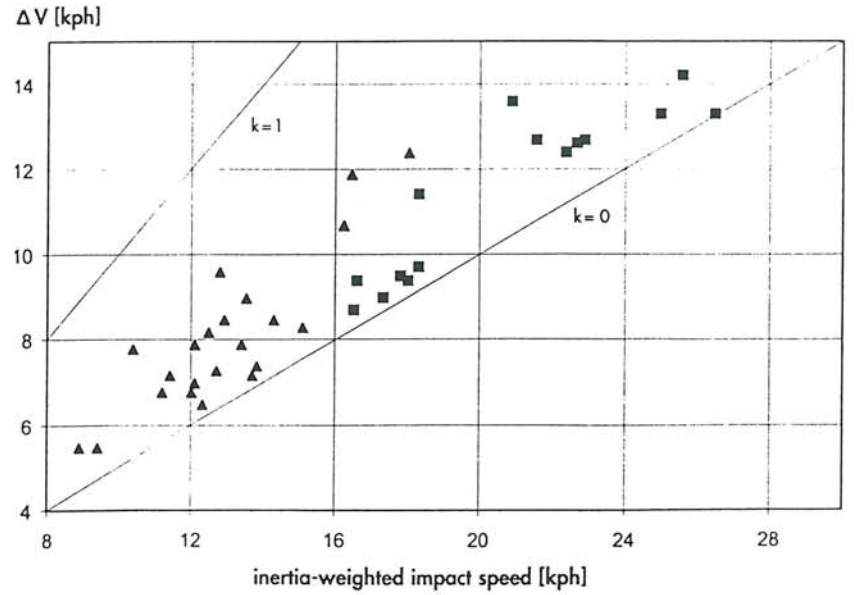

Fig. 9 Change in speed due to the collision (ΔV) in relation to the inertia-weighted impact speed v_i (boundary cases: k = 0: plastic collision; k = 1; elastic collision)
■ = Study 1997; ▲ = pre-study 1993

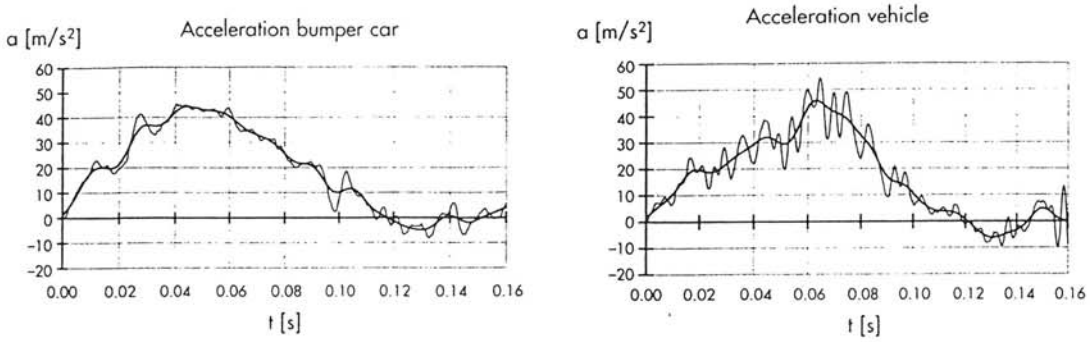

Fig. 10 Comparison of the acceleration signals from the bumper car *(left)* and automobile *(right)*

backward in the bumper car, the peak acceleration values of the head are significantly lower.

Technical collision parameters

Figure 9 documents the inertia-weighted impact speed via the velocity change due to collision for all the crash tests. The inertia-weighted impact speed neutralizes the influence of differences in vehicle weight and is thus more suitable for comparing collision processes.

The inertia-weighted impact speed of the bullet car ranged from 16.4 km/h to 26.4 km/h (average 20.9 km/h). The change in velocity ranged from 8.7 km/h to 14.2 km/h (average 11.4 km/h). The mean acceleration of the target car ranged from 2.1 g to 3.6 g (average 2.7 g). The impact speed of the bullet bumper car ranged from 11.0 km/h to 13.5 km/h (average 12.2 km/h). The change in velocity ranged from 8.3 km/h to 10.6 km/h (average 9.9 km/h). The mean acceleration of the target bumper car ranged from 1.8 g to 2.6 g (average 2.2 g). The velocity change of the test vehicles due to collision could be precisely calculated by integrating the acceleration signals from the passenger compartments over time.

Comparison of the acceleration signals between automobile and bumper car collisions resulted in very similar curves (Fig. 10). Deviations were seen only in head acceleration as a result of unrestricted head motion in the bumper car.

Results of the examinations of the test subjects

Evaluation of the physical examinations at time 2 (i.e., 18–25 h after the crashes) revealed that one female and four male test subjects reported symptoms. These were as follows:

Test subject 1 (female; age 37; Δ V *13.6 km/h)*: sensation of muscle soreness in the cervical spine for 3 days. Clinical examination: at the endphase of left rotation in inclination the test subject experienced a painful sensation.

Test subject 2 (male; age 47; Δ V *11.4 km/h)*: sensation of muscle soreness in the cervical spine, and lumbar spine complaints. Clinical examination revealed no pathologic findings in comparison to the clinical examination before the crash.

Test subject 3 (male; age 30; Δ V *12.6 km/h)*: headache persisting for 13 h after the crash and a sensation of muscle soreness in the cervical spine persisting until the 7th day. Clinical examination: facet joint C1/2 rightsided painful on pressure without an articular dysfunction.

Test subject 4 (male; age 30; Δ V *14.2 km/h)*: nausea and vomiting ½ h after the crash (this test subject had received malaria prophylaxis shortly before the experiment) and a sensation of muscle soreness in the cervical spine. Clinical examination revealed no pathologic findings in comparison to the clinical examination before the crash.

Test subject 5 (male; age 28; Δ V *12.7 km/h)*: headache and pain in the thoracolumbar spine persisting for 4 h after the crash. Clinical examination revealed no pathologic findings in comparison to the clinical examination before the crash.

Evaluation of the computer-assisted motion analyses of the cervical spine at time 2 (i.e., 18–25 h after the crashes) failed to confirm any changes caused by the accident.

MRI findings at time 2 (i.e., 20–28 h after the crashes) were identical to the previous studies. No signs of injury were demonstrated in the structures visualized. Of the seven test subjects (i.e., eight collisions) in whom preliminary MRI studies revealed degenerative changes, three reported symptoms after the crash and four (i.e., five collisions) did not. Two of the remaining nine test subjects without degenerative changes (i.e. in 3 out of 19 test subjects no MRI images were available) also complained of symptoms after the crash; seven did not.

Evaluation of examinations at time 3 revealed that, of the test subjects who initially reported symptoms, only test subject 2 still experienced any. These symptoms consisted of slightly restricted left rotation of about 10°, particularly in flexion. Symptoms in test subjects 4 and 5 disappeared entirely after 1 day; test subject 3's symptoms disappeared within 7 days. Those test subjects who were free of symptoms at time 2 were also free of them at time 3. However, the computer-assisted motion analysis of the

cervical spine showed changes in all test subjects in at least one direction of motion, although up till now no definite trend was discernible.

MRI findings were identical to those in previous studies. This final examination also failed to demonstrate evidence of trauma.

Discussion

The goal of this interdisciplinary study was to determine clinical and MRI changes following rear-end collisions in healthy volunteer test subjects, and to determine the precise pattern of motion of the passenger. In addition to this, rear-end automobile collisions were compared with rear-end bumper car collisions.

In the literature, there are a number of experimental studies [1, 4, 7–9, 11–14, 17, 20] in which test subjects were exposed to a rear-end collision. Significant injuries have not been reported to date. The disadvantage of almost all of these studies is the insufficient stress (low ΔV) and/or the lack or insufficiency of clinical and diagnostic imaging studies of the test subjects. Only Szabo and coworkers [17] conducted six two-car rear-end collisions with volunteers between the ages of 27 and 88 who underwent MRI and CT examinations before and after the tests. ΔV in these tests was approximately 8 km/h. Four of the five test subjects reported transient headache immediately after the stress, which rapidly disappeared. One female test subject complained of a stiff neck the next morning. Imaging studies showed degenerative changes, yet they failed to show any evidence of trauma after the stress. Even in our studies with a ΔV of up to 14.2 km/h and mean acceleration up to 3.6 g, the specific clinical and MRI examination before and after the rear-end collisions failed to demonstrate persistent symptoms or changes on MRI. Only five test subjects reported symptoms after the car collision. Pain did not persist longer than 1 week, and occupational disability did not result. The velocity change due to collision exceeded 11 km/h with these test subjects.

Motion analyses of the test persons during the entire collision phase revealed the trend that the maximum resulting relative angle between the upper body and the head increases with the increase in the horizontal distance between the back of the head and the headrest. However, hyperextension of the cervical spine, which has been discussed in the literature [10, 19] as a possible cause of injury, definitely does not occur in vehicles equipped with headrests at a ΔV of up to 15 km/h. This finding concurs with the data of Szabo and Welcher [18], who also failed to observe hyperextension. A notable finding in our examination was the extent of the relative translational motion between the upper body and the head (phase 3 of the motion analysis). The significance of such a translation as a possible cause of injury is not yet clear. Penning [10] noted a correlation between translation and subsequent stress of the upper cervical spine. He advanced the hypothesis that posterior hypertranslation of the head can lead to hyperflexion of the craniocervical region with risk of injury. The secondary motion can be excluded as a possible cause of injury since significant stresses do not occur in flexion of the cervical spine.

In real accident situations people often apply their brakes during the impact. From the work of Kalthoff [5] it is known that the stresses (i.e., ΔV) for the affected person in a braking target car is somewhat lower (on average 1 km/h) than in a target car without brakes applied. Bumper cars on the other hand can roll away easily after the impact. This difference was taken into account in our study. All the target automobiles had their handbrakes applied. Nevertheless, the comparison of the stress data of bumper car and automobile collisions shows that the passengers are subjected to comparable stresses. This confirms the analogies derived in the 1993 study by Meyer et al. [8, 9].

In contrast to the automobile tests, the motion analyses of the test subjects in the bumper car tests showed significantly higher values for the extension of the cervical spine (a maximum of 47° in automobiles as compared to a maximum of 80° in bumper cars). Despite this, none of these test subjects experienced subsequent symptoms. This fact also suggests that extension of the cervical spine cannot be as significant in causing injury as was previously assume. Given that the sitting posture in the bumper car is less favorable for the body, it is all the more surprising that "whiplash injuries" among bumper car drivers, with the exception of an 8-year-old girl [6], are not described in the literature, although innumerable rear-end collisions that often involve velocity changes exceeding those in traffic accidents occur daily in amusement parks. It is difficult to estimate the extent to which psychological components of so-called "post-traumatic stress syndrome" [15] are significant for traffic accident victims. A prospective study on this subject is currently being conducted.

Conclusions

1. The biomechanical "limit of harmlessness" in two-car rear-end collisions lies at a velocity change due to collision (ΔV) of between 10 and 15 km/h. Morphologic and anatomic signs of injury to the cervical spine cannot be demonstrated up to this speed range. At present, it is difficult to ascertain the extent to which psychological stresses are present or occur that can lead to persistent symptoms in victims of accidents involving a velocity change below this limit.
2. The extent of damage to the cars involved is crucial to determining the velocity change due to collision.

3. From preliminary results of the on-going motion analysis it can already be concluded that hyperextension of the cervical spine does not occur in rear-end automobile collisions involving velocity changes of up to 15 km/h if headrests are installed.
4. From a biomechanical perspective, automobile rear-end collisions are comparable to bumper car rear-end collisions.

Acknowledgement The authors thank the Bertelsmann Foundation for the financial support given to this study.

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