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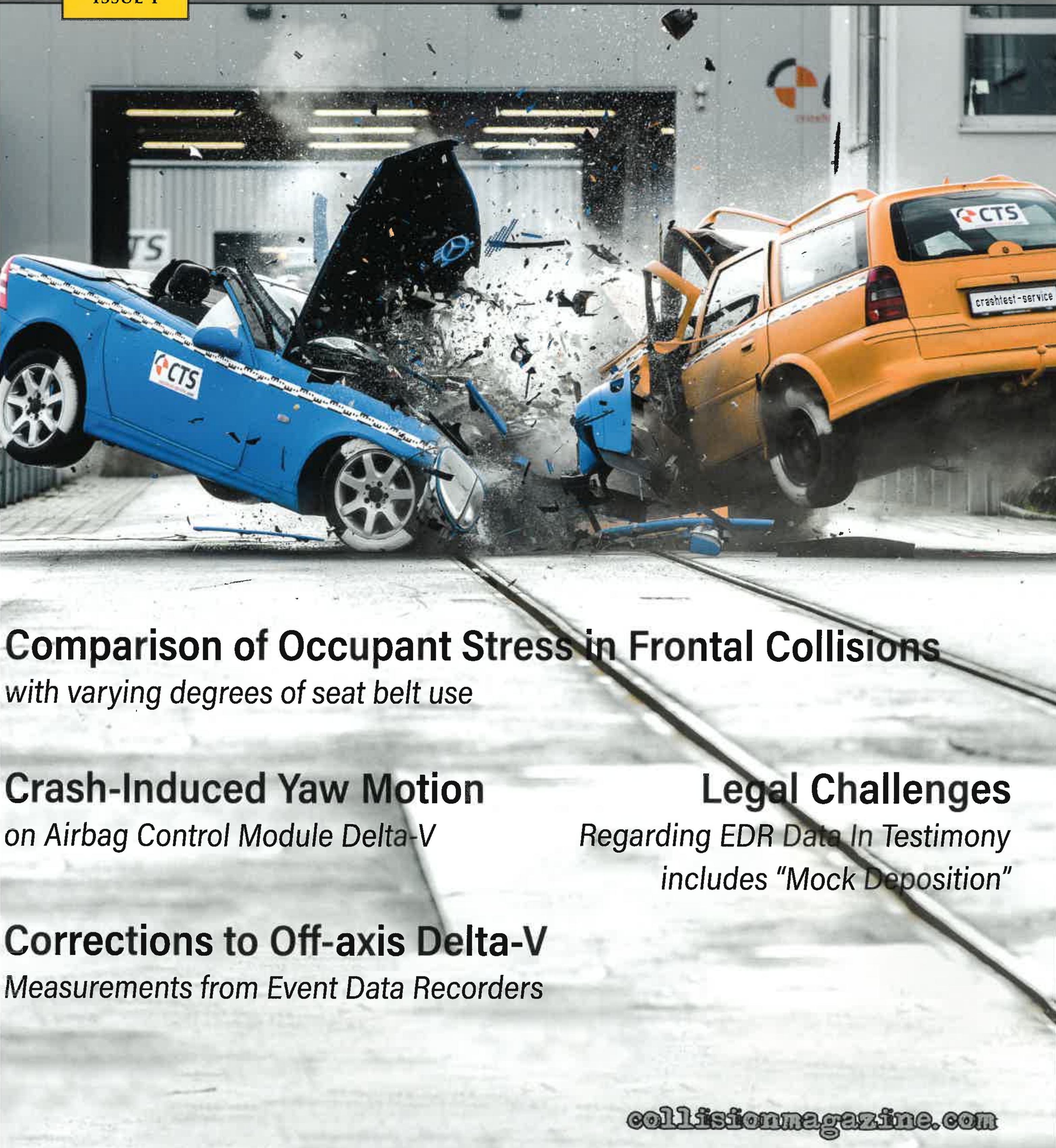

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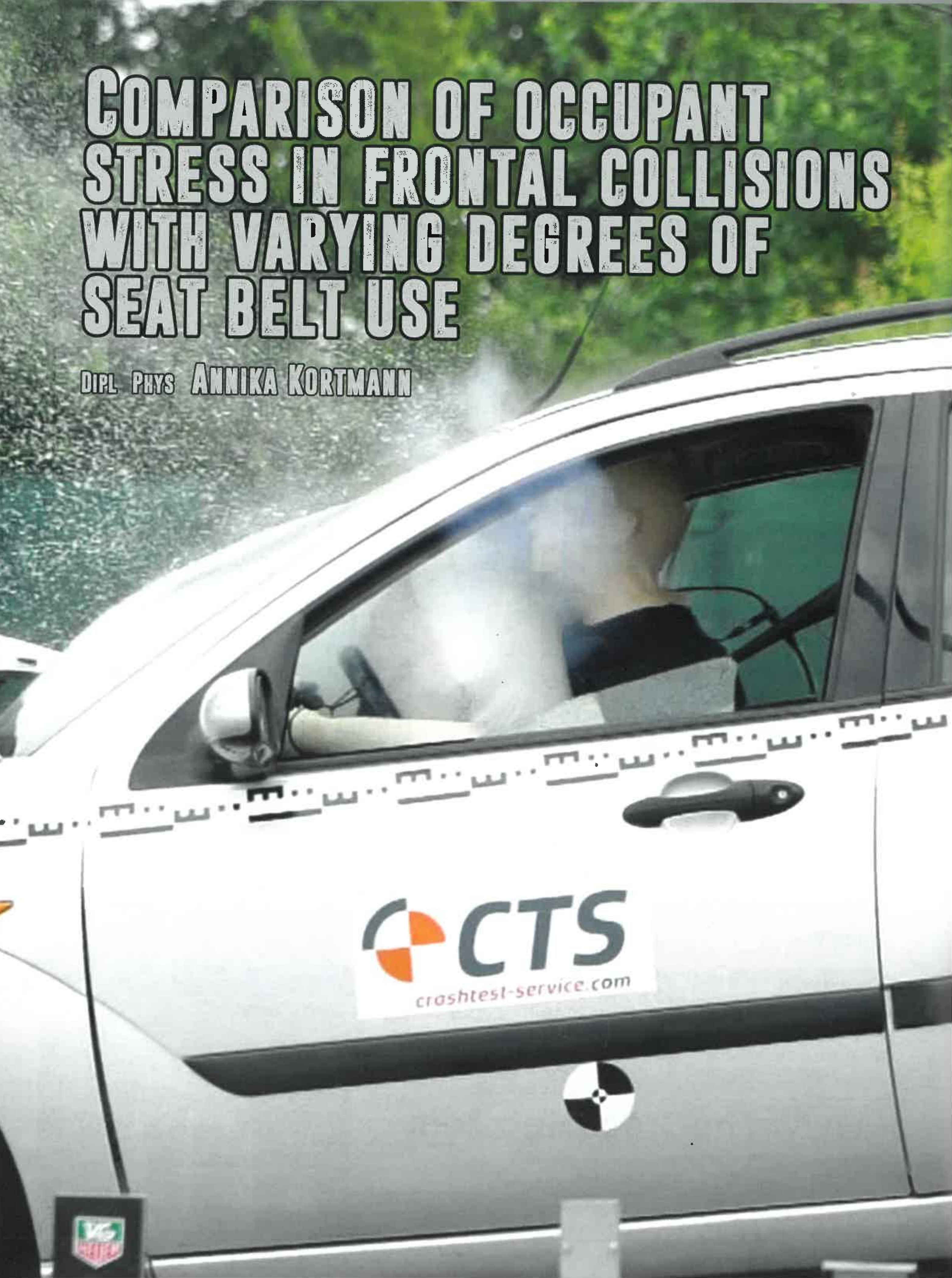
COMPARISON OF OCCUPANT STRESS IN FRONTAL COLLISIONS WITH VARYING DEGREES OF SEAT BELT USE

DIPL PHYS ANNIKA KORTMANN



The biomechanical stress on an occupant in a head-on collision is not only linked to the cabin acceleration of the passenger compartment. Where an airbag is activated, the seat belt and the airbag work together to reduce the relative forward motion of the occupants in the vehicle and minimize the risk of an impact with the vehicle interior. What stress such an impact has on the head, chest, and hips of a passenger and to what extent the improper use of the seat belt affects the biomechanical stress has not yet been tested and examined by accident reconstruction experts. For this reason, a series of experiments were conducted in which a Ford Focus traveling at 50 kph had a head-on collision with a tree and the acceleration sequence of the driver upon collision was measured using a biofidelic dummy fitted with measurement instruments. A total of three tests were performed, in the first test the dummy was not wearing a seat belt, in the second test the chest strap was worn just under the left shoulder and in the final test the three-point safety belt was used correctly. The results obtained are discussed and compared depending on the degree of use of the seat belt.

Introduction

A common issue in the reconstruction of accidents is the determination of the biomechanical stress on occupants during a vehicle collision. Known studies (see for example [1,2,3,4,5,6], carried out in cooperation with medical experts showed a connection between the cabin acceleration or change in velocity of the passenger compartment as a result of the collision and the biomechanical stress on the passengers. Tests on volunteers were used to test low-impact rear, front and side collisions. In practice, the load on the occupants was determined by technical experts, who calculated, for example, the vehicle's average cabin acceleration or the corresponding change in velocity upon collision so that medical experts could use this information to interpret the risk of injury.

The actual acceleration of the head, chest, or hips of the occupant is not taken into account in most cases as the rate of cabin acceleration was determined from the vehicle damage. In the case of low-impact collisions, the average cabin acceleration was then correlated with the injuries suffered by the passengers involved in the voluntary tests.

In contrast, there are almost no comparable tests using volunteers for high-impact collisions, such as those that activate the airbag, as the risk of injury is too high. It has only recently become possible to use biofidelic dummies in accident reconstruction, which, in addition to their humanoid physiognomy and comparable movements, can also be equipped with measurement instruments. The acceleration is recorded through triaxial accelerometers in the head, chest and hips, which record at 20,000 Hz (Figure 1). A separate accelerator compares the cabin acceleration of the passenger compartment and records these values synchronously with those of the sensors in the dummy.

Was the passenger wearing the seat belt properly?

In high-impact frontal collisions (e.g., impact with a tree at 50 kph), the question regularly arises, especially before the courts, as to whether the occupant was wearing their seat belt correctly and, if not, which injuries still would have been suffered had the occupant been wearing their seat belt properly.

If experts have access to photos of the vehicle involved in the accident, they may be already able to make a statement about the occupant's seat belt usage from the position of the seat belt or the deformation of the steering wheel. A seat belt that is firmly locked on the B pillar might indicate that the seat belt was not on at the time of impact and the seat belt pretensioner had locked the seat belt to the B pillar when the ignition was turned. According to Walter [7], an investigation of the seat belt itself in combination with the change in velocity determined to have resulted from the collision also offers an indication of whether the seat belt was used.

If such photos are not available or if they are inconclusive, medical experts would have to evaluate the severity of passenger injuries to determine whether the seat belt was used. From a technical perspective, it would therefore be beneficial to have some publicly available test results comparing head-on collisions that occur under the same conditions (collision speed, type of vehicle, impact configuration, etc.) where the only difference on the movement of the occupants and the resulting stress was the use of the seat belt (seat belt used/seat belt not used). This would make it possible to directly compare the effect of a collision on an occupant who was wearing a seat belt and one who was not.

Unfortunately, no such tests were available.

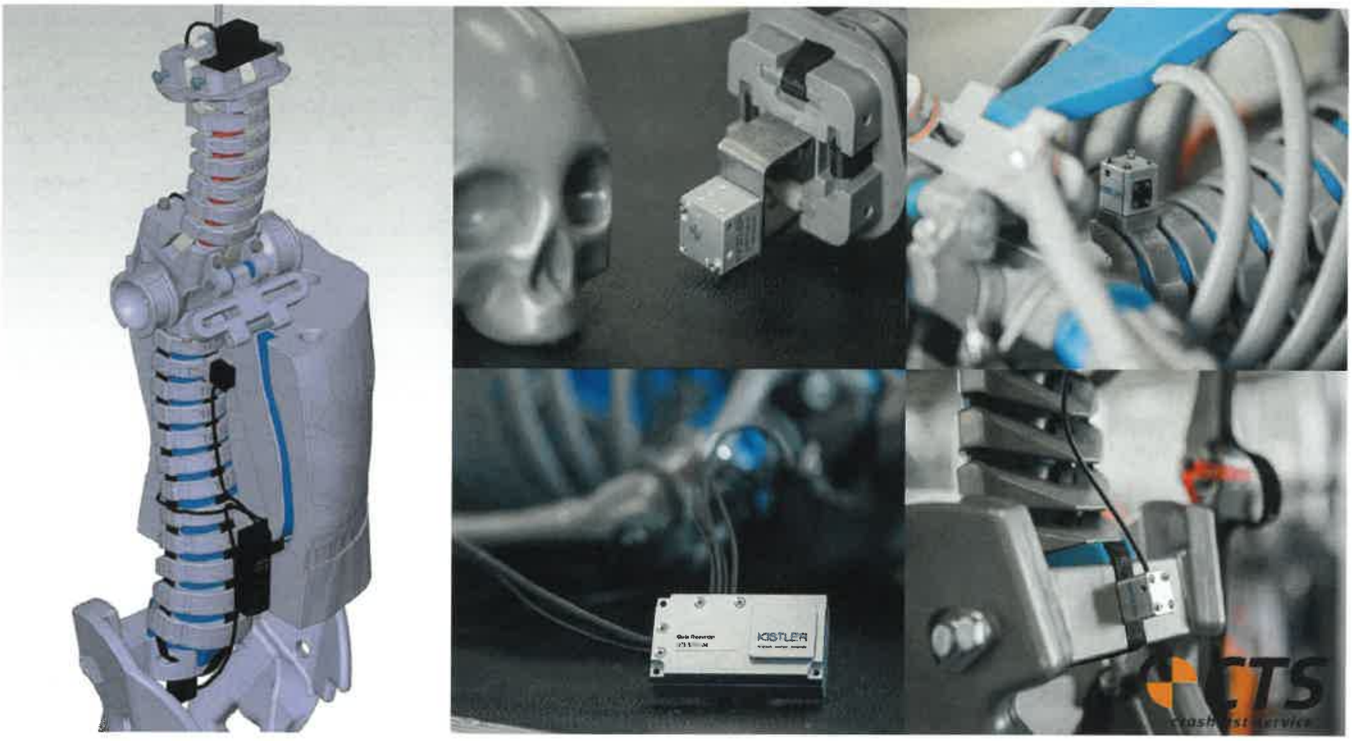


Figure 1: Positioning of the triaxial accelerometers in the PRIMUS

Figure 2: Collision configuration for the series of tests with a head-on collision with a tree accounting for 40% coverage of the vehicle (left) and the PRIMUS dummy used for the tests, positioned in the vehicle (right)

Figure 3: Degree of seat belt use for the tests: not wearing a seat belt (left), the chest strap worn under the left shoulder (middle), and the seat belt worn correctly (right)

Structure of the series of experiments

A research project with the company crashtest-service.com GmbH (CTS) on the validation of the biofidelic PRIMUS [8] made it possible for the first time to carry out an investigation into the above topic, in cooperation with the engineering firm Schimmelpfennig + Becke.

Three tests were carried out in which a Ford Focus traveling at approximately 50 kph was driven head on into a tree accounting for 40% coverage of the vehicle. The collision configuration can be seen in Figure 2. In all three tests, a PRIMUS dummy equipped with instruments was placed in the driver's seat to determine the head, chest and hip acceleration throughout the course of the collision. The acceleration of the passenger compartment was measured using an additional accelerometer between the front seats in the center console, at the height of the center of gravity and the results were correlated with the data measured by the dummy.

For the tests, only the level of seat belt usage of the dummy varied. All other parameters remained the same. The differences in seat belt use of the dummy are depicted in Figure 3: not wearing a seat belt, seat belt worn under the left shoulder, and seat belt fitted properly. The test with the seat belt worn under the shoulder is designed to test the effect of a seat belt worn "poorly or in-correctly" on the passenger stress.

Implementation and analysis

Figure 4 shows a side view of the motion sequences of the dummies in a collision at the same points in time. In the red vehicle, the dummy is unbelted; in the silver vehicle, the dummy is wearing the seat belt under the shoulder (hereinafter referred to as "poorly belted"); and in the blue vehicle, the seat belt is being worn correctly (hereinafter referred to as "properly belted").

A clear difference can be identified in the occupant movement in the case of the unbelted dummy (red vehicle). Unrestrained, the dummy's chest collided with the steering wheel and before its head struck the roof edge and then windshield. Optically, there is almost no difference between the poorly belted dummy and the one with the seat belt worn properly (silver and blue vehicles respectively). The upper body of both occupants is obviously restrained by the seat belt. The locking mechanism of the hips of the dummies and the lap strap cause the upper bodies of both dummies to rotate forwards and downwards so that both dummies hit the opening airbag with their head.

The comparison of the acceleration sequence of the passenger compartment in the x-direction for all three tests as depicted in the diagram in Figure 5 shows that all three crash tests can be directly compared to one another. In all three tests, the passenger compartment shows a change in velocity of around 55 kph as a result of the collision. The damage to the vehicles also corresponds optically to one another (Figure 6). The following diagrams are filtered by CFC60 (Channel Frequency Class). The customary filtering by CFC1000 for head acceleration does not provide any additional relevant information for this test so that the CFC60 filter was used instead for illustration.

As the acceleration sensors in the dummy and the passenger compartment are measured via the same module, it is possible to synchronize each acceleration in time with one another. The resulting acceleration sequences for the three tests are juxtaposed against one another in Figure 7. This sets out the passenger compartment acceleration (gray) in relation to the head (red), chest (blue) and hip acceleration (green). The acceleration is given in g ($g = 9.81\ m/s^2$).

From this juxtaposition, it is immediately clear that in the case of an occupant who is not wearing a seat belt or one who is not wearing it properly, there is a higher head acceleration (or to be precise, excessively high deceleration) (red graph), which does not occur in the case of an occupant with a seat belt worn properly. The deceleration of the occupant is delayed compared to the deceleration of the passenger compartment. The occupant is only connected to the vehicle through the seat belt. The delay of approximately 0.02 s before the deceleration of the occupants in the case of occupants who are wearing a seat belt can be explained by the slack in the seat belt. The tighter the seat belt, the earlier it will force the occupant to change movement in line with the movement of the passenger compartment.

In the case of the unbelted occupant, it is the collision of the occupant's head with the steering wheel or the roof liner after approximately 0.06 s that first causes the body to decelerate.

After further analysis of the acceleration sequences, it seemed sensible to look at the acceleration of each part of the body separately and to compare these depending on the level of seat belt use.

Evaluation of the head acceleration

To compare the resulting acceleration sequences of the heads of the differently retrained occupants, the effect of the acceleration on the head is depicted in x-, y- and z-directions for each test and then correlated with the movement of the occupants based on each frame.

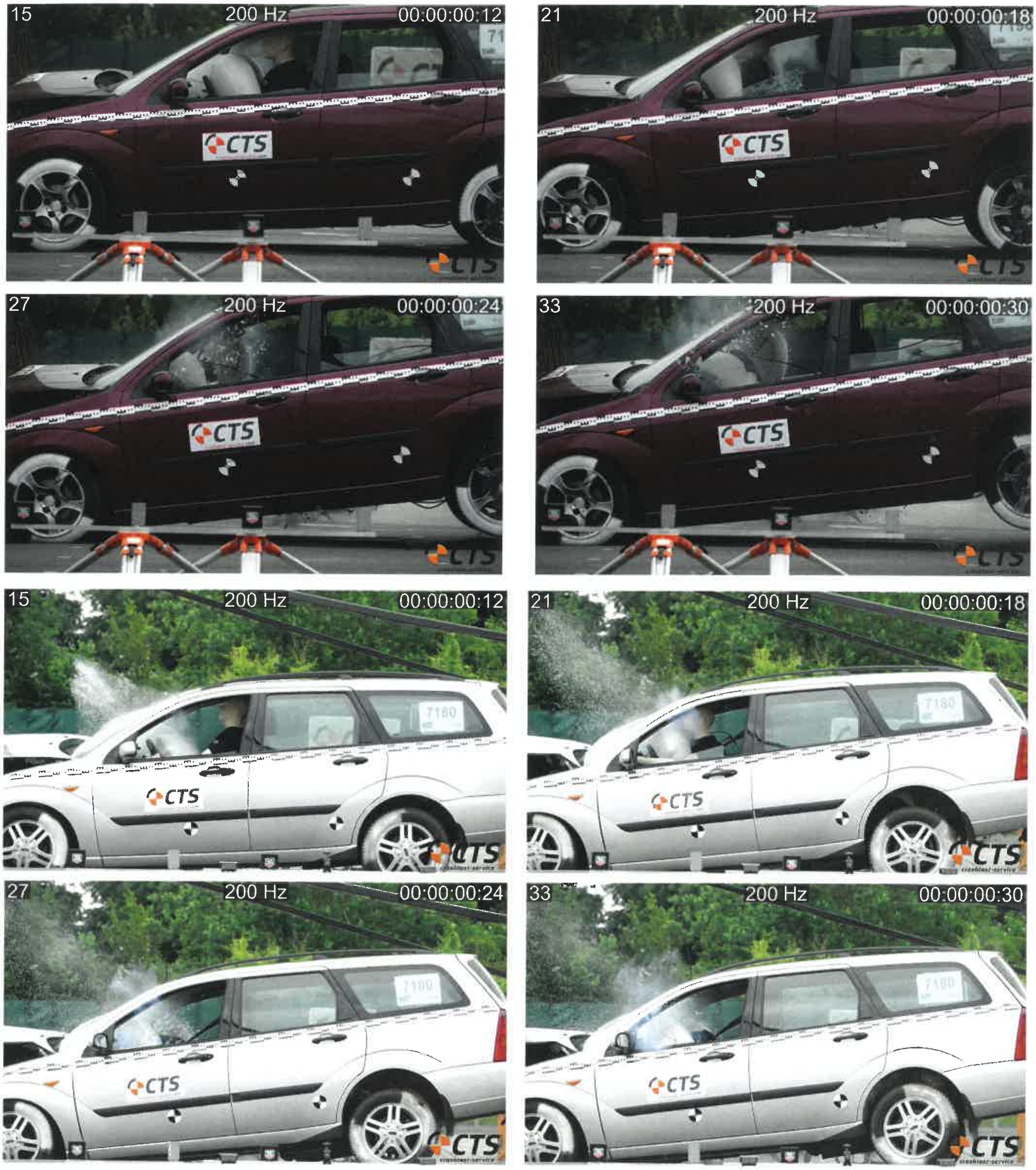


Figure 4: Motion sequence for unbelted (top), poorly belted (bottom) and properly belted PRIMUS (next page)

Figure 4 (cont.): Properly belted PRIMUS

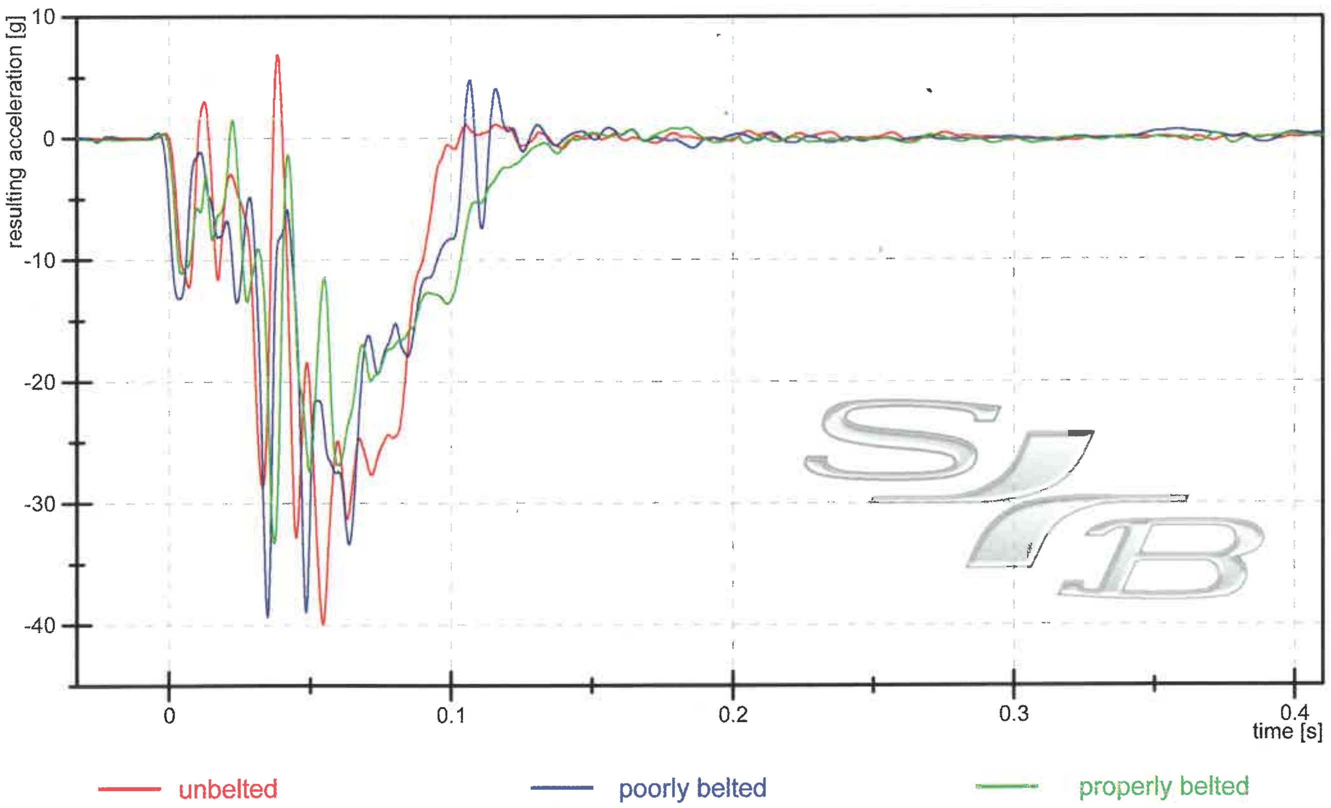


Figure 5: Acceleration sequences of the passenger compartment of the crash vehicles in the x-direction

Figure 6: Comparison of the damage to the vehicles used for the crash tests

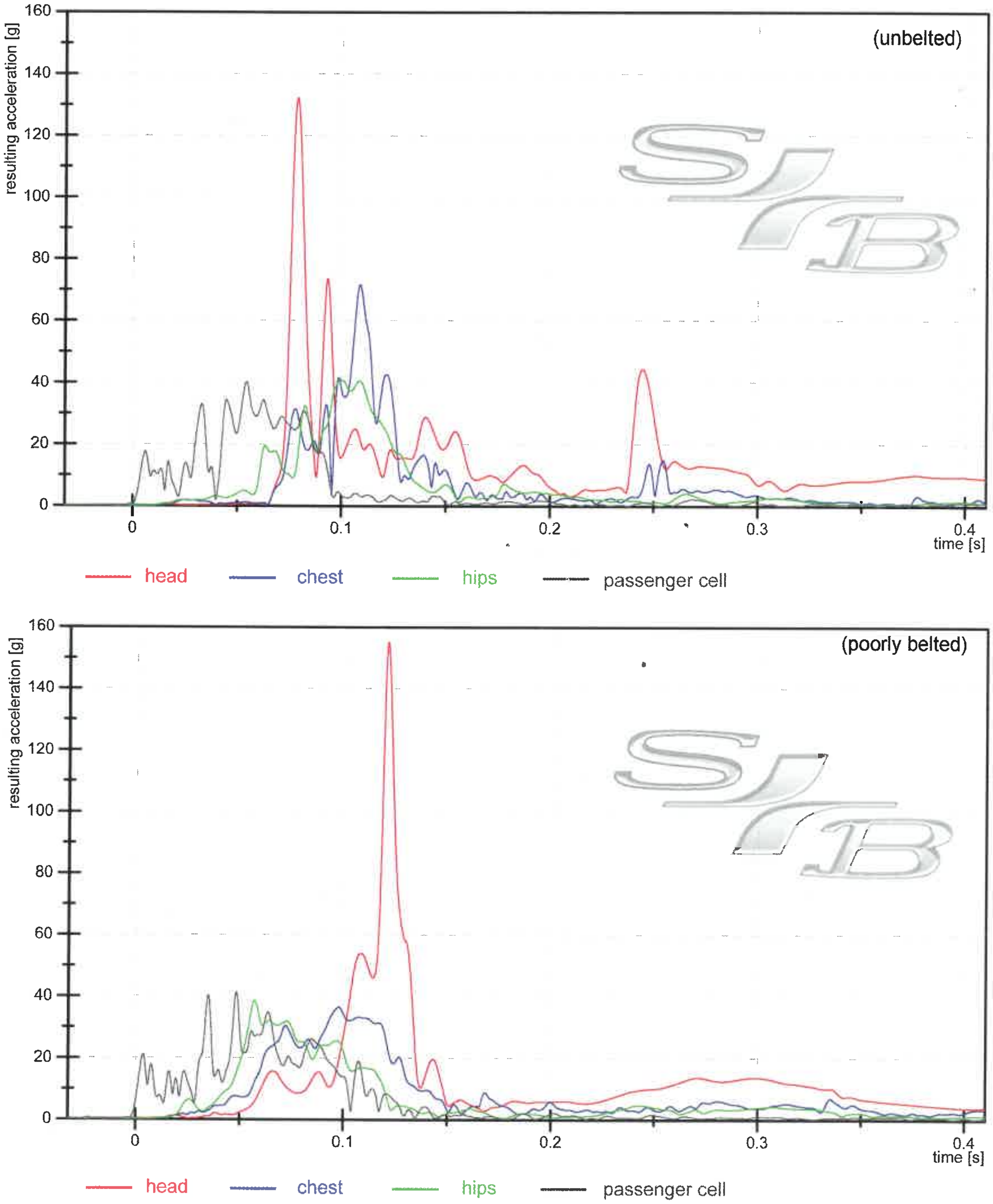


Figure 7: Comparison of the resulting acceleration of the head (red), chest (blue), hips (green), and the passenger cell (gray) for the varying degrees of seat belt use by the occupants

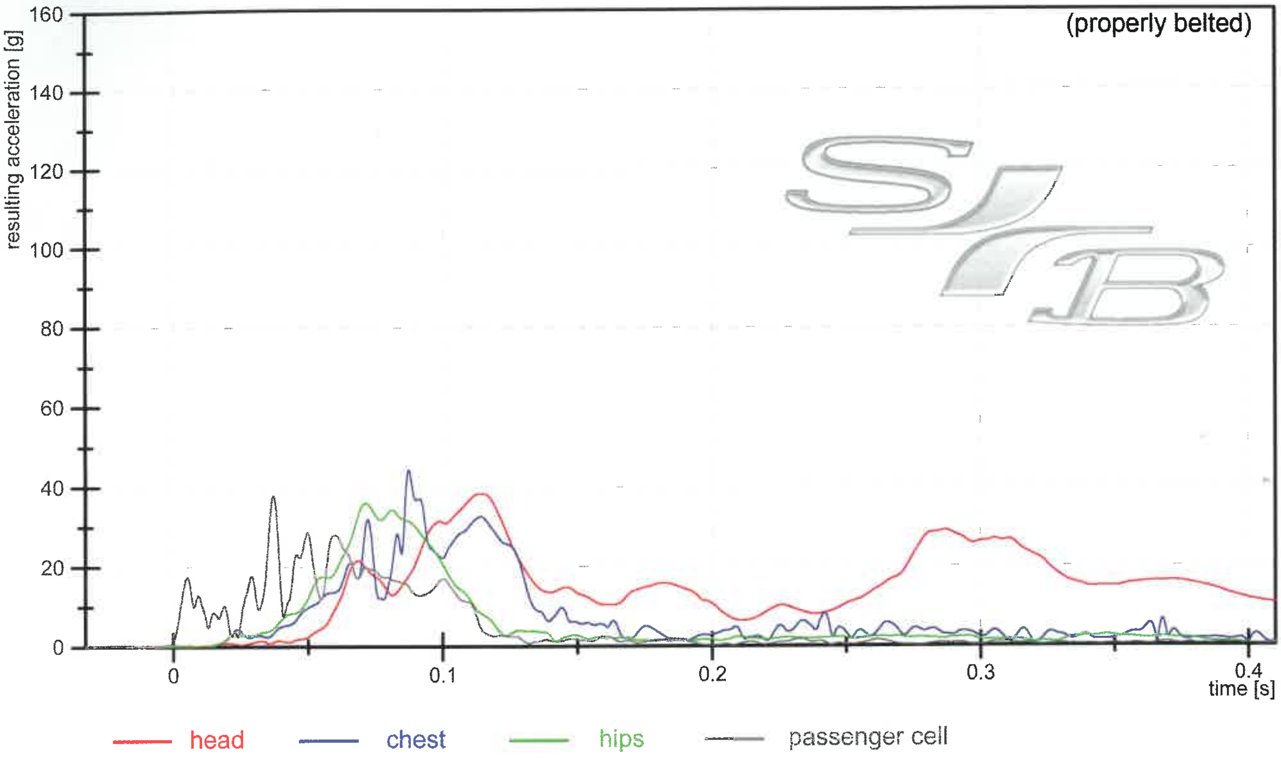


Figure 7 (cont.): Comparison of the resulting acceleration of the head (red), chest (blue), hips (green), and the passenger cell (gray) for the varying degrees of seat belt use by the occupants

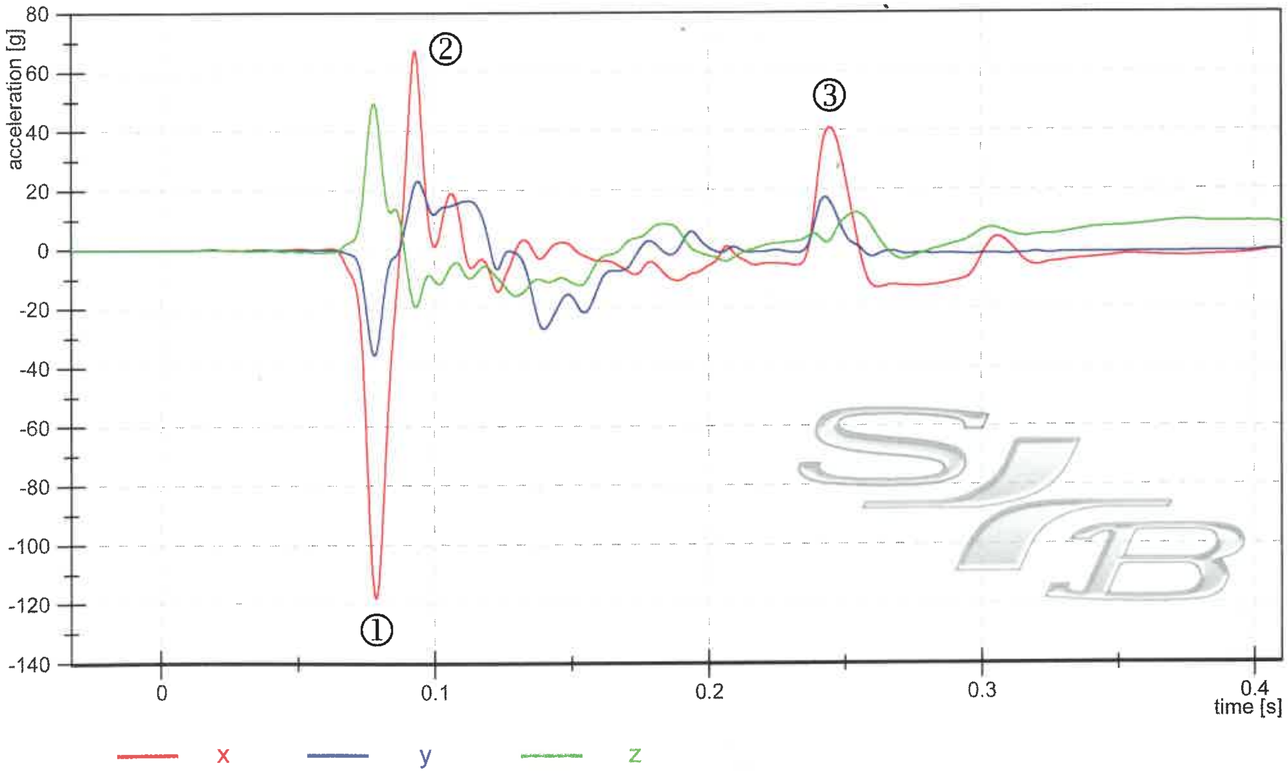


Figure 8: Head acceleration of the unbelted occupant in x-, y- and z-directions

Figure 9: Multiple impacts of the head of the unbelted occupant with the roof edge (1), the windshield (2) and the roof liner (3)

Figure 8 graphically plots the acceleration sequence of the head of the unbelted occupant in x-, y- and z-directions against time. In the x-direction (red graph), three marked peaks can be identified, which have been numbered consecutively. The peaks can be allocated to the movement of the occupants based on time (Figure 9). The first peak is the impact of the occupant's forehead with the roof edge. With an impact time of 0.023 s, an average deacceleration of 46.36 g (454.79 m/s^2) can be derived from the graphs. The integration of the acceleration over the extremely short impact time results in a change of velocity of the head upon collision of 36 kph. All further measurements of the collision time t, maximum and average acceleration (a_{max} and a_{avg}), and the change in velocity resulting from the collision Δv are summarized as an overview in Table 1 at the end of the article.

The head subsequently snaps backwards so that the occupant hits the windshield with their face (second peak). In this phase, during a collision time again of 0.23 s, the average acceleration was 23.14 g (227.00 m/s^2), which equates to a change in velocity of 18.72 kph caused by the collision.

After hitting the windshield, the occupant bounces back into the vehicle interior and hits their head on the roof liner from below at around 0.25 s after the start of the collision (third peak).

Figure 10 depicts a similar analysis assigning the acceleration peaks with the occupant's movement for the occupant who is wearing their seat belt incorrectly, while the related occupant movement is depicted in Figure 11. The first peak arises when the movement of the head decelerates after 0.1 s due to the airbag. A further 0.02 s later, the head is severely slowed. The head still hits the steering wheel although the airbag activated and although the occupant was using the lap strap fully and the chest strap partially.

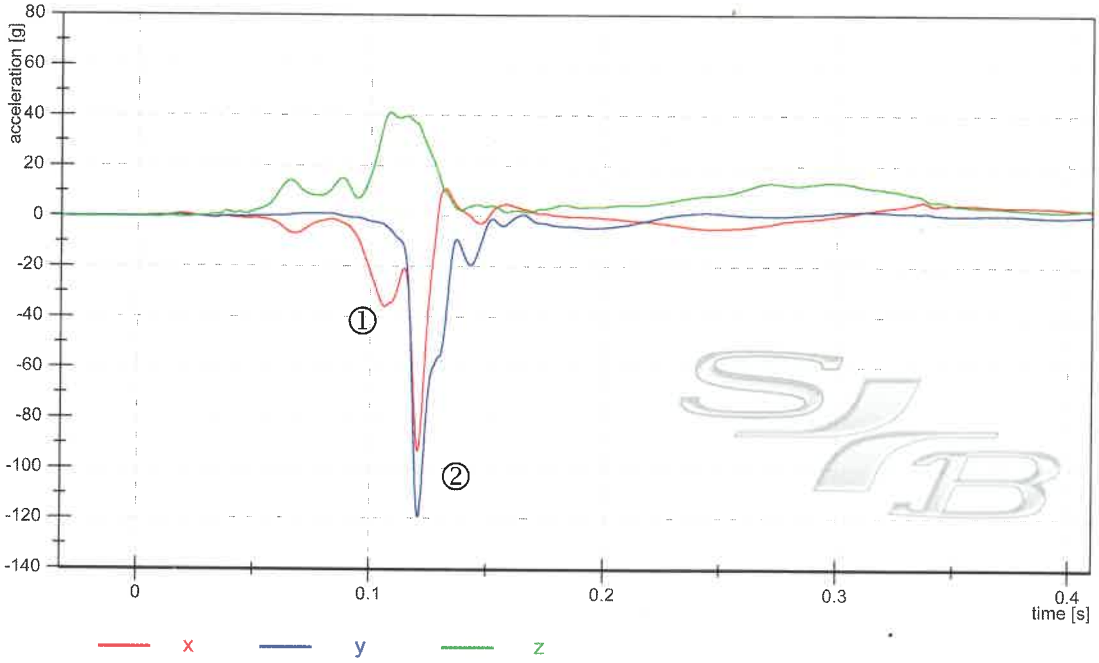


Figure 10: Head acceleration of the poorly belted occupant in x-, y- and z-directions

Figure 11: Impact of the poorly belted occupant with the airbag (1) and the steering wheel (2)

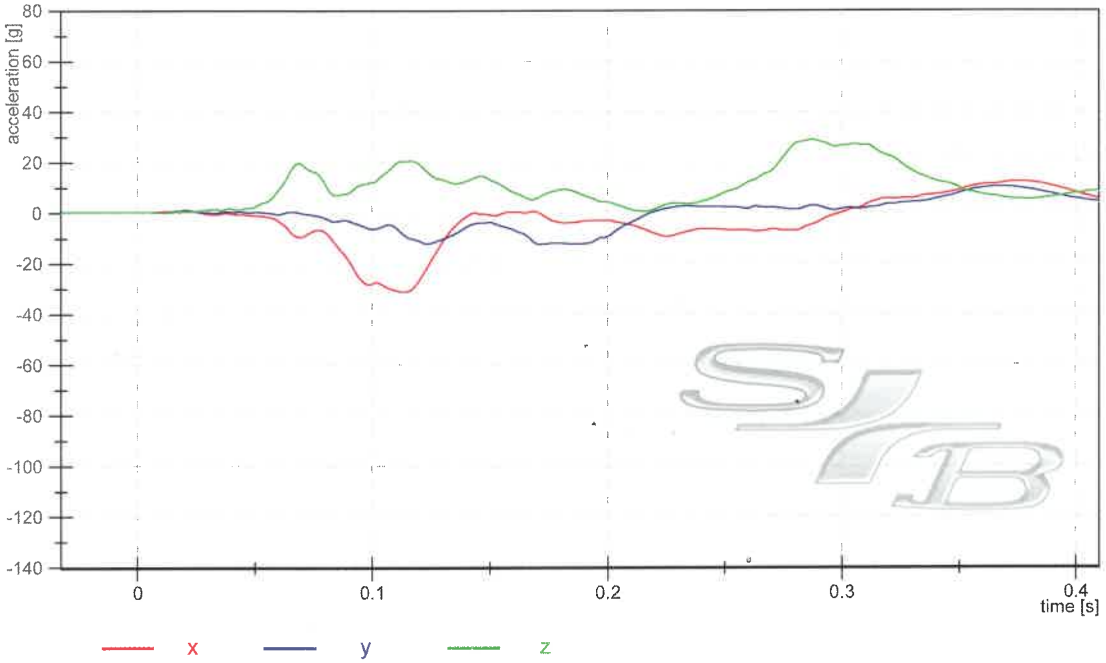


Figure 12: Head acceleration of the properly belted occupant in x-, y- and z-directions

The average acceleration is approximately one-third of the acceleration of the unbelted occupant when they hit the roof edge with their head (14.27 g/139 m/s^2), see Figure 8.

If one depicts the acceleration sequence of the head for the occupant with the seat belt worn properly (Figure 12), there are none of the brief, strong peaks in acceleration as are noted for the occupants who were not wearing a seat belt or not wearing it properly. Instead, the head merely experiences a deceleration of up to 32 g. The head also decelerates over a comparatively long time of 0.12 s. This longer deceleration time is achieved through the combination of the airbag and the chest strap. The change in velocity of 50.15 kph caused by the collision is comparable to the impact of the head on the steering wheel of the occupant who was not wearing their seat belt correctly. However, the longer duration results in a lower average deceleration of 11.87 g (116.44 m/s^2).

The comparison of the resulting deceleration of the head depending on the seat belt use is shown in Figure 13. The airbag alone is not sufficient to "softly" decelerate the head. If the upper body is not sufficiently restrained by the chest strap, the head will hit the steering wheel despite the activated airbag. Figure 14 shows an enlarged excerpt of the deceleration since the start of the collision (enlarged to 0.2 s). The acceleration sequences of the head of an occupant who is poorly belted (blue) and whose seat belt is worn properly (green) are in close approximation for up to 0.1 s after the collision. After that, the chest strap of the occupant who

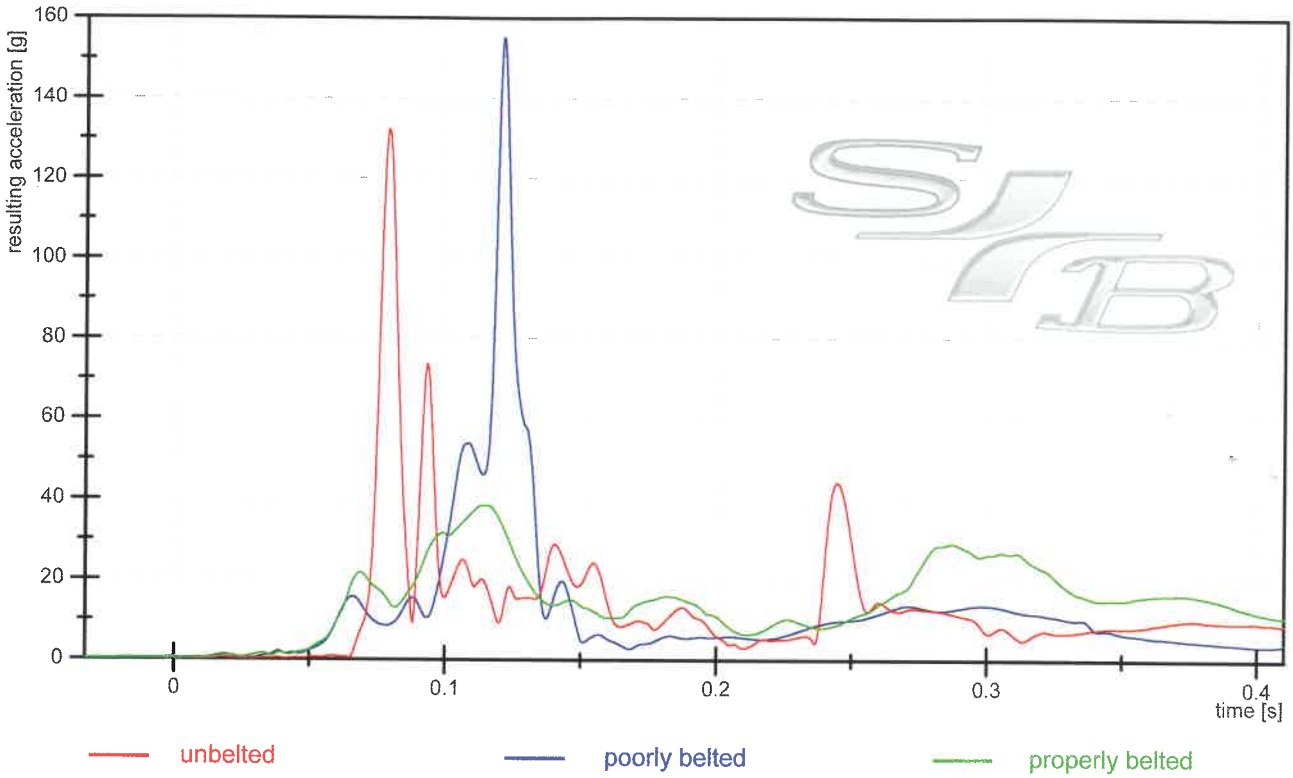


Figure 13: Comparison of the resulting head acceleration depending on the degree of seat belt usage

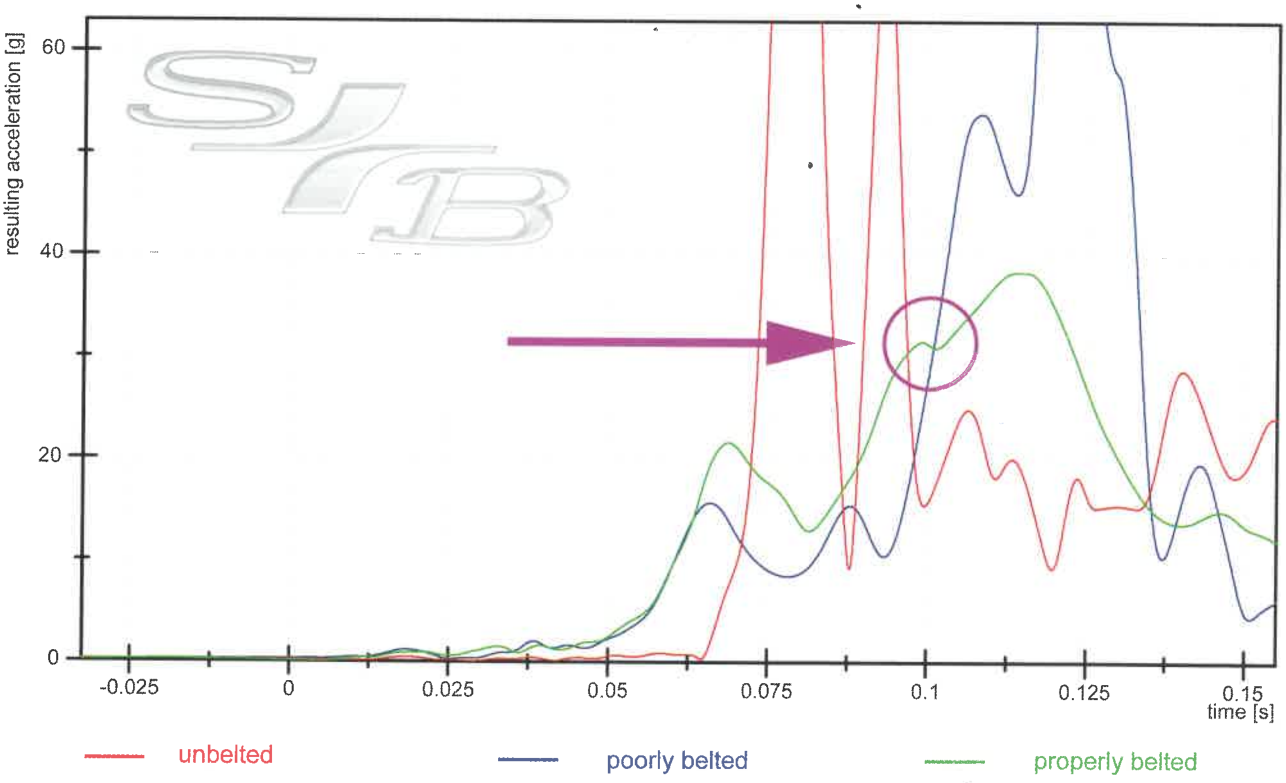


Figure 14: Enlarged excerpt of Figure 13

is poorly belted slips further away from the left shoulder so that the seat belt no longer sufficiently restrains the upper body (indicated in magenta). While the head of the properly belted dummy only decelerated slightly quicker, the airbag collapses in the case of the poorly belted dummy because the airbag could not effectively stop the head and the chest at the same time. As a result, the head impacts with the steering wheel.

If one evaluates the change in velocity of the head as a result of the collision for the poorly belted occupant and the occupant with a seat belt worn properly, it shows that the head experiences a loss in velocity of 105±3.5 kph in both cases as a result of the collision. However, the maximum deceleration a_{max} for the occupant who is not wearing the seat belt properly is around four times larger, while the average deceleration a_{avg} is approximately twice as large.

Head rotation when immersing in the airbag

The diagram in Figure 12 shows that, despite the frontal collision, the occupant also experiences deceleration in y- and z-directions, which can be quite significant. This is

Figure 15: Significant rotation of the head when immersing in the airbag (properly belted)

because of the head movement of the occupant, which was recorded using an onboard camera in the case of the occupant with the seat belt worn properly (Figure 15).

As the head immerses in the airbag, it rotates significantly. Individual images show that the left shoulder of the occupant is restrained by the seat belt. The right shoulder swings forward, resulting, among other things, in the rotation of the upper body. The head follows this rotation, so that airbag no longer slows the head just from the front but from the right side of the head, too.

Evaluation of the chest acceleration

The diagram in Figure 16 applies the resulting acceleration sequence of the chest depending on seat belt usage. There is almost no difference in the acceleration sequence of a poorly belted dummy (blue) compared to the dummy with the seat belt worn properly (green). The occupants are essentially held by the lap strap and the upper body cannot reach the steering wheel, regard-less of how the chest strap is sitting. The maximum deceleration in the range of 35 to 44 g occur. With an exposure time of 0.14 or 0.17 s, this results in a loss of velocity from the collision of 76.64 or 84.41 kph, with an average deceleration of 15.50 or 13.74 g respectively.

Where the occupant is not wearing a seat belt, the occupant moves forward freely within the vehicle. For that reason, the deceleration of the upper body is clearly delayed compared to the occupants who were wearing a seat belt. The acceleration sequence of the chest of the unbelted occupant is shown for each direction in Figure 17. In the x-direction (red graph), there are two characteristic deceleration peaks. The impact with the airbag accounts for first peak (Figure 18). A short time later, the airbag collapses and the chest collides with the steering wheel (second peak). When colliding with the steering wheel, the occupant experiences a change in velocity of 76.74 kph (Figure 16) as a result of the collision. The change in velocity is therefore comparable to the change in velocity in the case of an occupant who was wearing a seat belt. However, in the case of an impact with the steering wheel, the maximum delay is approximately two times larger and the deceleration time is accordingly low.

Evaluation of the hip acceleration

As expected, there is also no noteworthy difference in the resulting hip acceleration of the dummies depending on the position of the chest strap (Figure 19 blue/green graph) as both dummies are restrained by the lap strap in the same way. At 71.34 and 65.90 kph respectively, the change in velocity of the hips as a result of the collision is close to the change in velocity of the passenger compartment (78.75 and 63.75 kph) because the hips are directly attached to the vehicle through the lap strap, apart from a small amount of slack in the seat belt.

In the case of the unbelted occupant, the deceleration of the hips is delayed because the lap strap does not decelerate the hips directly; instead, it is the impact of the chest

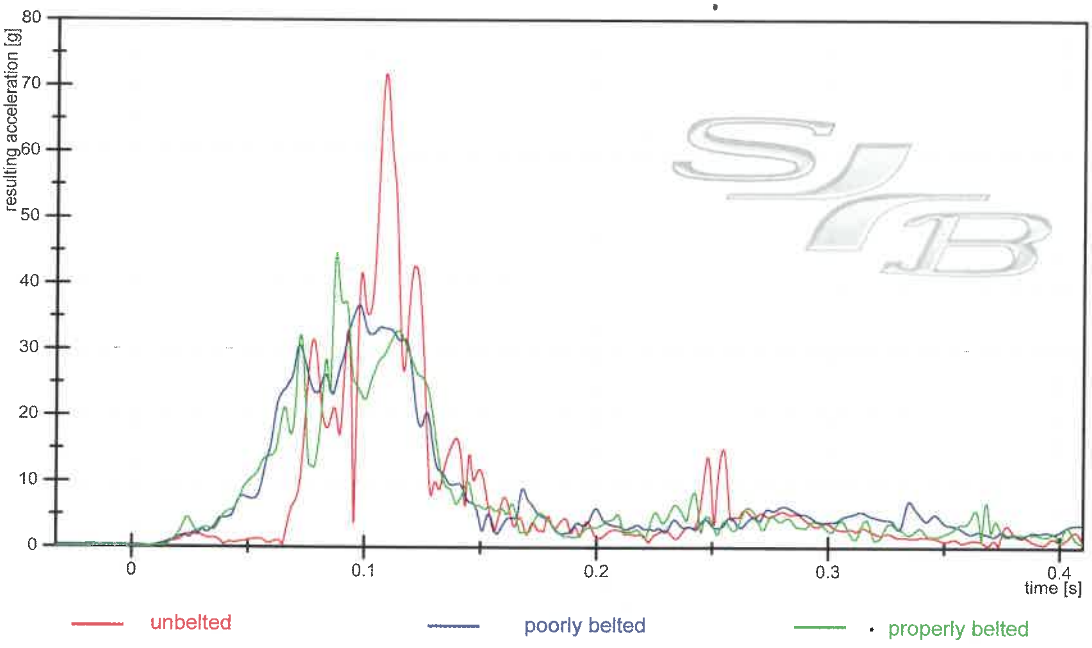


Figure 16: Comparison of the resulting chest acceleration depending on the degree of seat belt usage

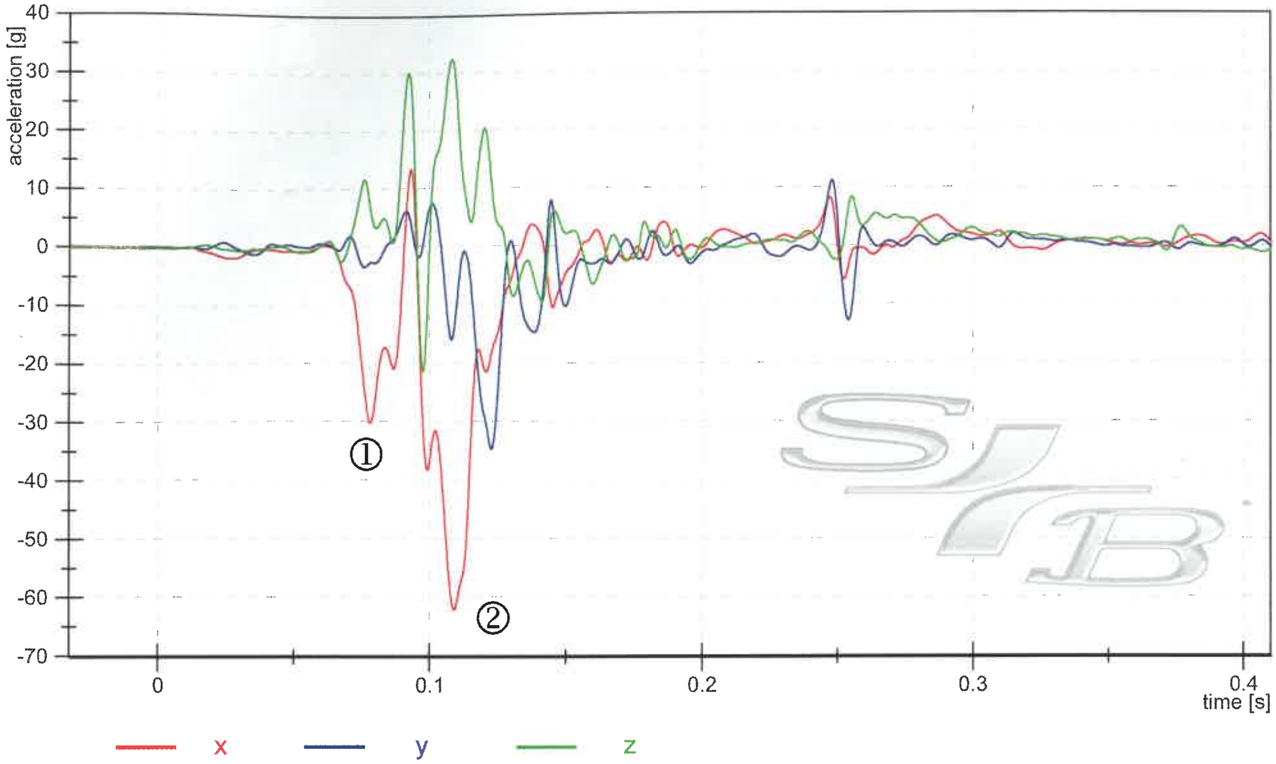


Figure 17: Chest acceleration of the unbelted occupant in x-, y- and z-directions

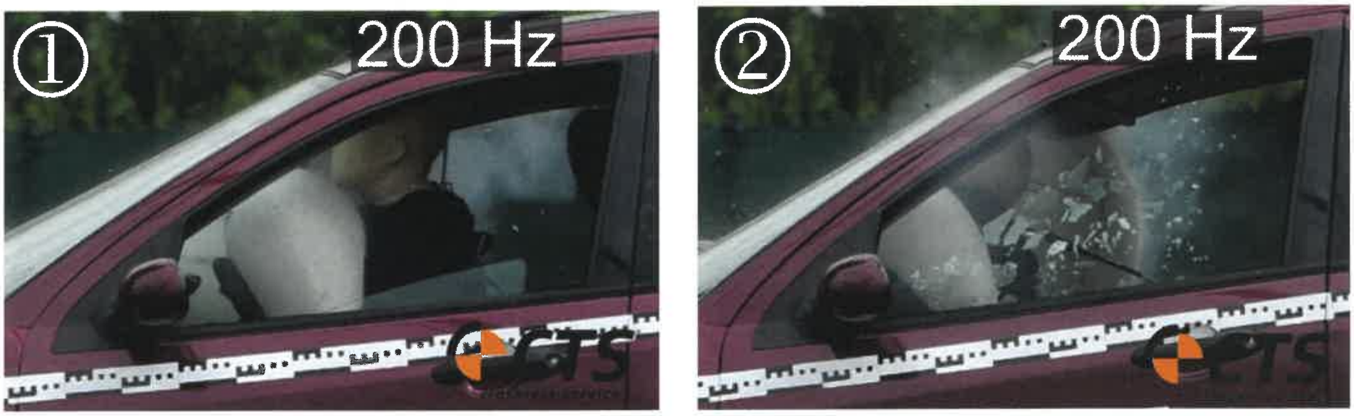


Figure 18: Chest impact of the unbelted occupant with the airbag (1) and the steering wheel (2)

first with the airbag and then with the steering wheel that results in the deceleration. As the dummy's hips do not impact directly with the vehicle in this case, the resulting change in velocity of the hips is only 36.38 kph.

Comparison of the injuries

The biofidelic sensors of the PRIMUS dummy which was used not only made it possible to record the acceleration sequences of each area of the body, but they also allowed for an "autopsy" of the dummy to be conducted after the test to reveal the injuries of the occupants.

The autopsy showed that the unbelted occupant suffered massive hyperextension of the cervical vertebrae and a break in some thoracic vertebrae (Figure 20). The hyperextension resulted from the motion sequences outlined above (Figures 4 and 9). In comparison, the dummy that was not wearing the seat belt properly suffered two broken ribs on the left side, an injury to the elbow joint on the right, and ligament sprains in both knees (Figure 21).

A comparison of the injuries suffered by the unbelted dummy and the poorly belted dummy shows that the amount of the stress incurred is not the only significant element. Although the duration and the level of acceleration

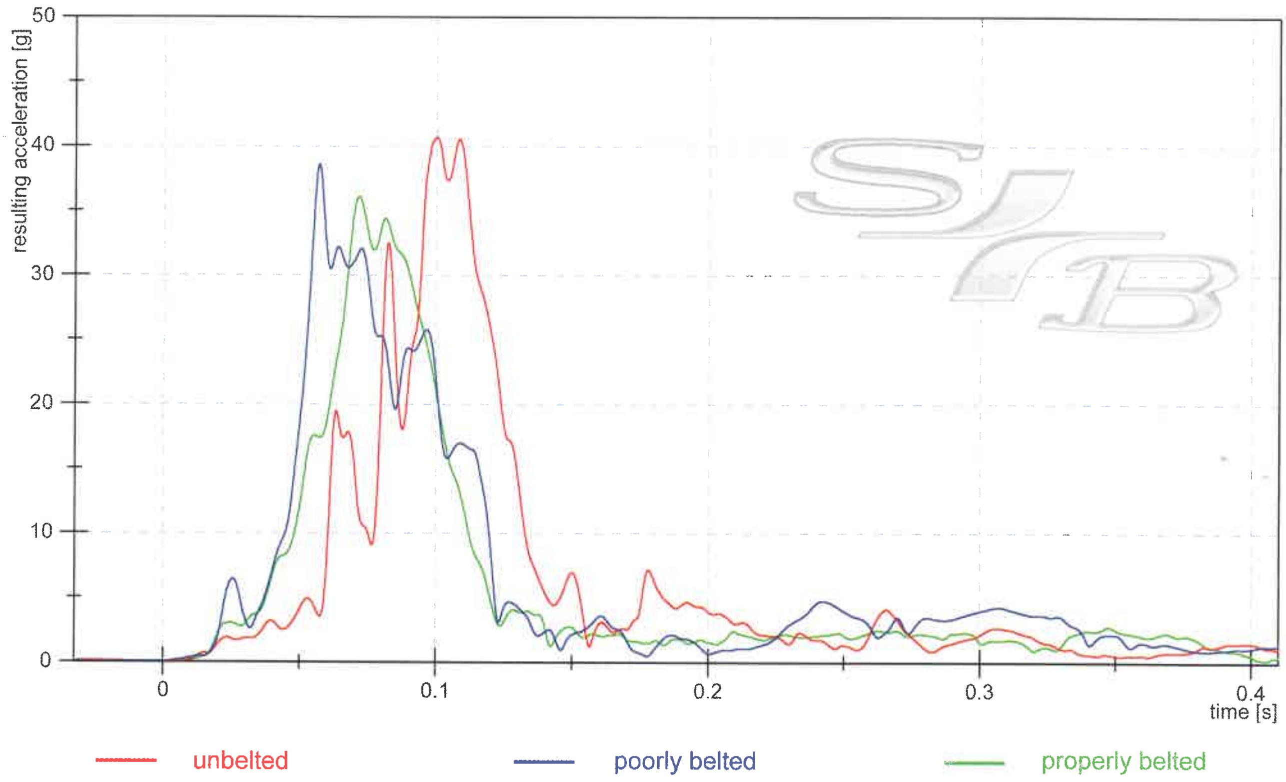


Figure 19: Comparison of the resulting hip acceleration depending on the degree of seat belt usage

	sensor	direction	t [ms]	a_{max} [g]	a_{avg} [g]	a_{avg} [m/s²]	Δv [kph]
unbelted	**head**	x (roof edge)	23	-	46,36	454,79	36,00
		x (windshield)	23	-	23,14	227,00	18,72
		res	-	-	-	-	-
	chest	res	87	71,71	25,06	245,84	76,74
	hips	res	155	-	6,65	65,24	36,38
	vehicle	x	133	-	11,73	115,07	55,09
		res	135	-	15,09	148,03	71,86
poorly belted	**head**	x (steering wheel)	94	-	14,27	139,99	47,32
		res	102	155,14	30,04	294,69	108,40
	chest	res	140	36,60	15,50	152,06	76,64
	hips	res	155	-	13,03	127,82	71,34
	vehicle	x	132	-	11,74	115,17	54,74
		res	135	-	16,52	162,06	78,75
properly belted	**head**	x (airbag)	120	31,46	11,87	116,44	50,15
		res	162	38,43	17,69	173,54	101,40
	chest	res	174	44,40	13,74	134,79	84,41
	hips	res	155	-	12,06	118,31	65,90
	vehicle	x	132	-	11,66	114,38	54,39
		res	134	-	13,47	132,14	63,75

Table 1: Summary of the measured values and the resulting change in velocity for the series of tests

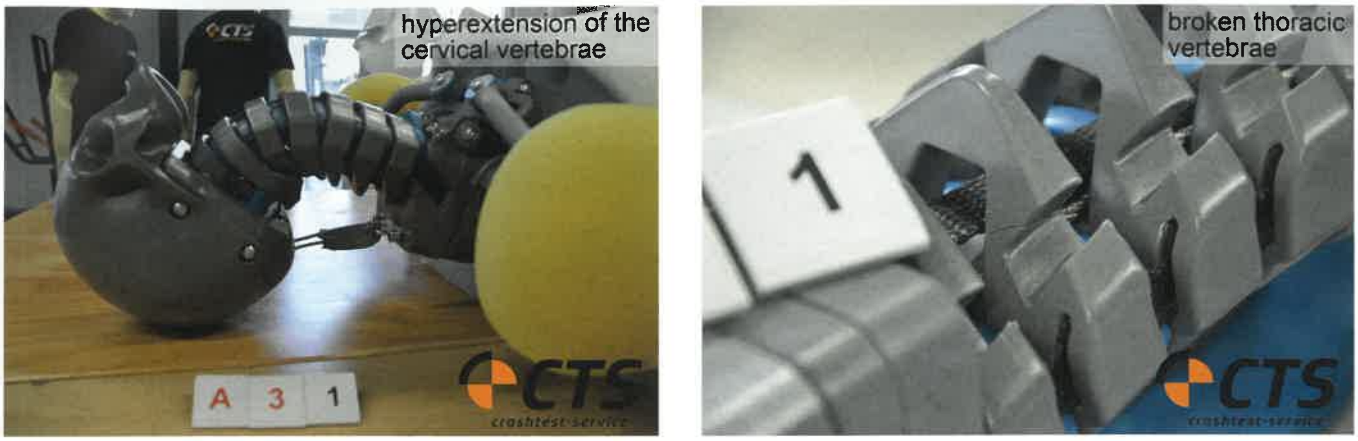


Figure 20: Injuries to the unbelted PRIMUS dummy

Figure 21: Injuries to the poorly belted PRIMUS dummy

differed significantly, the resulting change in velocity of the head arising from the collision was similar in both tests. However, the direction of the forces acting on the head resulted in the hyperextension of the cervical vertebrae in the unbelted dummy, while the poorly belted dummy hit the airbag front on with the head and then hit the steering wheel, with-out any significant hyperflexion or hyperextension of the cervical vertebrae.

The injuries of the PRIMUS dummy that was wearing a seat belt properly are depicted in Figure 22. The collision resulted in two broken ribs on the left side and a fracture of the sternum.

Figure 22: Injuries to the properly belted PRIMUS dummy

Summary

The use of PRIMUS dummies outfitted with biofidelic sensors and instruments now makes it possible for accident reconstruction experts to reproduce even severe collisions and to record the stress impacting directly on the occupants, even in scenarios where it is no longer safe to use volunteers for the tests. In addition, the subsequent "autopsy" of the dummy allows the injuries suffered in the form of broken bones, ligament sprains, etc., to be documented in a way that even non-specialists can understand.

> *The use of PRIMUS dummies outfitted with biofidelic sensors and instruments now makes it possible for accident reconstruction experts to reproduce even severe collisions and to record the stress impacting directly on the occupants, even in scenarios where it is no longer safe to use volunteers for the tests.*

The series of tests carried out involving a head-on collision of a Ford Focus traveling at 50 kph showed that the proper use of the chest strap has a considerable impact on reducing the stress suffered by the occupants. If the seat belt is not worn properly over the shoulder and slips during the collision, the airbag will no longer be able to sufficiently stop the head. The occupant will still hit the steering wheel with their head despite the deployment of the airbag. Where the seat belt is worn correctly, the upper body is restrained to the point that the head will be stopped over a longer period and at a lower level of deceleration. The resulting change in the velocity of the head caused by the collision in the case of the impact of the head with the steering wheel and the deceleration through the airbag is comparable at 105±3.5 kph. However, the differences in the duration and speed of the deceleration are significant.

A comparison of the injuries suffered by the unbelted dummy the poorly belted dummy shows that the amount of the stress incurred is not the only significant factor. Although the duration and the level of deceleration differed significantly, the resulting change in velocity of the head caused by the collisions was similar in both tests. However, the direction of the forces acting on the head resulted in the hyperextension of the cervical vertebrae in the dummy who was not wearing a seat belt, while the dummy that was not wearing the seat belt properly hit the airbag front on with the head and then hit the steering wheel, without any significant hyperflexion or hyperextension of the cervical vertebrae.

The evaluation showed that despite the fact that it was a frontal collision, there were also comparatively significant acceleration forces acting on the head area of the occupants in the y- and z-directions. This can be explained from the head movement of the occupant with the seat belt worn properly so that the left shoulder was restrained by the chest strap.

As expected, the change in velocities of the hips resulting from the collisions was almost equivalent to those of the passenger compartments, as the occupants who were wearing a seat belt were connected to the vehicle, apart from a small amount of slack in the seat belt.

Outlook

When evaluating the biomechanical stress on an occupant in a head-on collision, the collision can sometimes cause the front airbag to activate. At present, there are no comparable measurements available to show the extent to which an airbag reduces the stress on the head in the case of a frontal collision. Until now, experts were limited to using the collision-related change in velocity of the passenger compartment based on the damage to the vehicle in order to determine the biomechanical stress on the occupants.

In the future, the instrumented PRIMUS dummy will make it possible, for example, to test the effect of the partial activation of front airbags in a crash test involving a frontal collision and thereby ascertain the level of influence of the airbag on biomechanical stress.

I would like to thank crashtest-service.com GmbH for the excellent cooperation and Dr. Dobberstein in particularly for his comprehensive and quick evaluation of the various measurements.

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