Analyses of Thoracic and Lumbar Spine Injuries in Frontal Impacts

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Abstract

In general the passive safety capability is much higher in newer cars due to the stiff compartment preventing intrusions in severe collisions. However, the deceleration pulse becomes higher due to the stiff structure which leads to a change of injury patterns. Nevertheless, in frontal impacts without intrusions into the passenger compartment lumbar and thoracic spine injuries, covering burst, compression or dislocation fractures as well as soft tissue injuries, were found.

In order to analyse possible injury mechanisms for thoracic and lumbar spine injuries, data from the German In-Depth Accident Study (GIDAS) were used in this study. A two step approach of statistical and case-by-case analysis was applied for this investigation.

Thoracic and lumbar spine injuries such as burst, compression or dislocation fractures as well as soft tissue injuries were found to occur in frontal impacts even without intrusion to the passenger compartment.

In total 4,289 cases were selected including 8,844 vehicles, 5,765 injured persons and 9,468 coded injuries. If a MAIS 2+ injury occurs, then in 15 % of the cases a thoracic and/or lumbar spine injury is included. Considering AIS 2+ thoracic and lumbar spine, then most injuries were fractures and occurred in the lumbar spine area.

From the case by case analyses it can be concluded that lumbar spine fractures occur in accidents without the engagement of longitudinals, lateral loading to the occupant and/or very severe accidents with MAIS being much higher than the spine AIS.

Keywords Accident Analysis, Lumbar, Thoracic, Spine, Injuries, Frontal Impact

I. INTRODUCTION

With the introduction of lap belts a new injury pattern, the so called seat belt syndrome, was observed [1]. This injury pattern describes abdominal and lumbar spine injuries as a result of submarining. Today, better belt systems largely prevent submarining; however, spinal injuries are still observed. Since the introduction of UN Regulation 94 and consumer information programs, traffic safety has improved significantly in Europe due to improvements in education, primary and secondary vehicle safety, emergency services, and road infrastructure [2]. In particular, the secondary safety of vehicles has changed during the past years with the development of stable passenger compartments in order to avoid intrusion which was one of the major causes for contact injuries of belted occupants. Hence, the numbers of fatalities in the EU 27 have been decreasing in recent years.

However, this trend is less obvious for the number of severely injured car occupants. Recent accident studies on frontal impacts have shown that intrusion into the passenger compartment of newer vehicles occur less often compared to older vehicles, e.g. [3], [4], [5]. On the other hand, the deceleration pulse becomes higher due to the stiff structures which lead to a change of injury patterns [4]. One body region known to remain at a relatively high risk of injury, even in newer cars, is the thorax [5]. The injury mechanism for most thoracic injuries without intrusion is reported typically as direct loading from the restraint system. Nevertheless, lumbar and thoracic spine injuries were observed in frontal impacts without intrusions.

Richards et al. [6] reported that in total the spinal injuries were reduced due to the introduction of three-point restraint systems and airbags but still lower thoracic and upper lumbar spine fractures are documented in several studies [7], [8]. In [6] they investigated the injury mechanisms by conducting statistical analyses as well as sled testing. The results show that thoracolumbar injuries are often accompanied by an abdominal injury.

Ball et al. [7] also reported similar results from a retrospective case study of 37 patients that were involved in frontal impacts and had thoracic / lumbar injuries. They showed a reduced risk of abdominal and lumbar

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spine injury for 3-point belted occupants compared to occupants wearing a lap belt.

Jakobsson et al. [9] investigated AIS2+ thoracic and lumbar spine injuries in accidents involving Volvo cars during 1991 – 2005 and found 189 occupants who sustained spinal injuries from a subset of 21.034 adult occupants. Multiple events, run-off-the-road scenarios, and the role of both occupant characteristics as well as occupant posture during load transfer through the spine at impact were identified as important factors.

In crash tests belt forces are usually measured for monitoring purposes. It is known that the forces measured at the shoulder belt are typically in a range between 4 kN and 6 kN which corresponds to an acceptable thoracic injury risk for severe crash events [10], [11]. Moreover, there is a push to reduce the load, which is still often injurious to older occupants in relatively moderate collision severities. However, forces measured on the lap belt can be much higher. In Fig. 1 the belt forces measured in a full-width test with a supermini car at 50 km/h are shown. While the load limiter moderates the forces of the shoulder belt to approximately 5 kN, the outboard lap belt forces showed a steep increase with a maximum of approximately 10 kN.

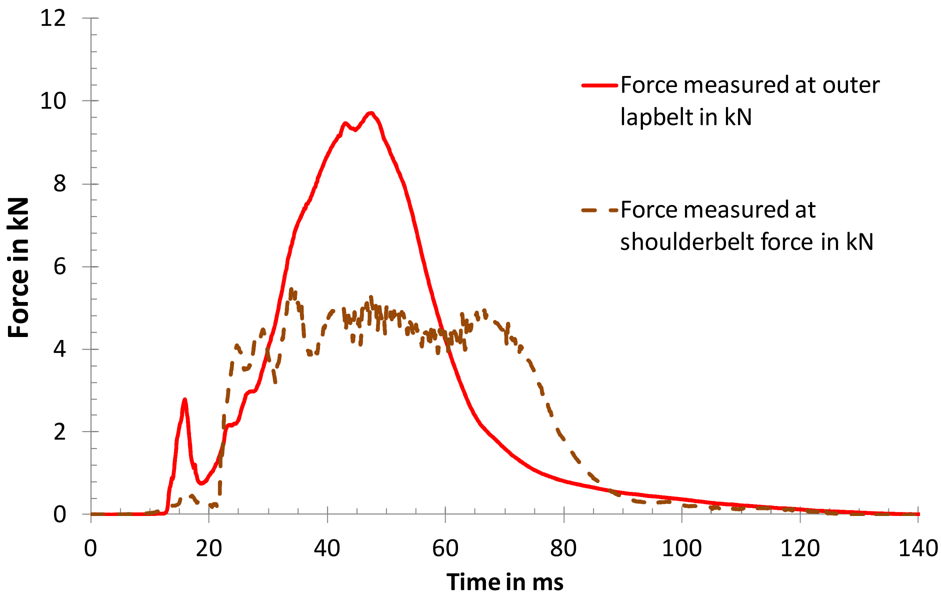

FIG. 1 BELT FORCES MEASURED AT THE DRIVER SIDE IN A FULL WIDTH TEST WITH A SUPERMINI CAR AT 50 KM/H

The seat structure is a fundamental component of the restraint system in a modern vehicle. Integrated seat ramps prevent the occupant from submarining beneath the lap belt but also induce additional pelvis restraint. An example of a seat structure in the rear seat row of a middle class vehicle is shown in Fig. 2. It can be seen that the type and the shape of the cross member can be expected to be very efficient to restrain the dummy pelvis in a frontal impact.

FIG. 2 SEAT RAMP INSTALLED IN A MIDDLE CLASS VEHICLE, BACK SEAT ROW

Regulatory and consumer crash tests do not assess the forces induced in the dummy bottom. Fig. 3 is an example of a seat structure that pushes through the seat cushion and produces remarkable damage to the dummy bottom. The crash test was performed at a speed of 56 km/h against the full-width deformable element

[12].

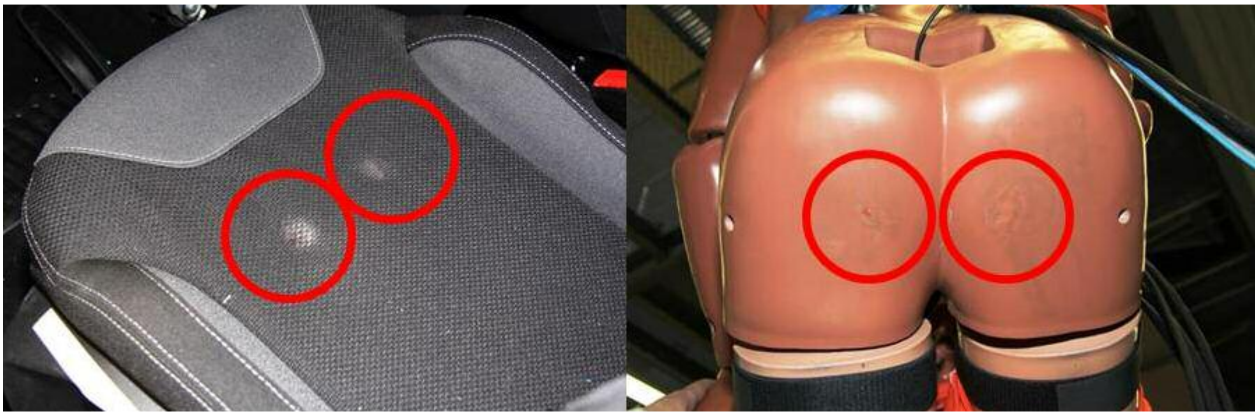

FIG. 3 CONTACT POINTS FROM THE SEAT PAN AND CORRESPONDING DAMAGES AT THE DUMMY BOTTOM IDENTIFIED AFTER A 56 KM/H CRASH TEST AGAINST THE FULL WIDHT DEFORMABLE ELEMENT

In general it can be concluded that lumbar spine injuries are still relevant and that several factors may lead to an increase of lumbar and thoracic spine injuries in the future:

- Recent cars are stiffer and the deceleration pulse will increase which causes a stronger restraint loading for the occupant;
- Following the knee modifier in Euro NCAP crash tests, it is likely that either knee airbags will be introduced or knee contact force to the dashboard will be reduced by other measures (such as increased pelvic restraint by lap belt and seat);
- While shoulder belt forces are usually within a range between 4 to 6 kN, lap belt forces exceeding 10 kN were observed in standard crash tests;
- Seat ramps are mounted in vehicles to prevent submarining. The design of the seat ramp influences the amount and direction of forces transferred into the pelvis and therefore also the lumbar spine. These forces are currently not assessed in standard crash tests.

Therefore, the objective of this study is to analyse spinal injury incidence with a focus on AIS 2+ injuries and to identify the underlying injury mechanisms with the use of road accident data. While most of the spinal injuries are located in the neck, these are normally reported as being distortions only and rated as AIS 1 injuries. When focusing on AIS 2+ injuries, these are mainly spinal fractures that are in most of the cases located in the thoracic and lumbar spine. Therefore, for this study neck injuries are excluded and the focus was on thoracic and lumbar spine injuries in frontal impacts.

II. METHODS

As the research question is very specific and the number of available in-depth cases is quite small, a two step approach of statistical and case-by-case analysis was applied for this investigation. In the first step a statistical analysis with the GIDAS data base was conducted to obtain a representative overview of the amount of lumbar and thoracic spine injuries in passenger car occupants involved in frontal impacts. The focus was on cases where either no or minor intrusions into the occupant compartment were detected and injuries occurred either due to inertial loading or were induced by the restraint system. The abbreviated injury scale (AIS) from 2005 was used to determine the injury severity [13].

In the second step a case-by-case analysis of the data sample was performed to investigate the injury mechanisms in detail. A selection of case parameters like accident type and character, crash object, change of velocity, seating position of the occupant and restraint system usage were evaluated. The interaction between the lower extremities and the dashboard as well as the performance of the restraint system was analysed in detail.

The **general data query** focused on frontal impacts of passenger cars (principle direction of force: 11, 12 and 1 o’clock), no rollover, occupants sitting on the driver or front passenger seat and occupants older than 12. Only cases where the car’s first registration was in 2000 or later were selected. Cars between 2000 and 2003 were checked individually in the case-by-case analysis to determine if they were UN Regulation 94 compliant. Only fully reconstructed accidents were considered with at least one injured person and which occurred between years 2000 – 2009.

Since mid-1999, the GIDAS (German In-Depth Accident Study) project investigates about 2000 accidents in the areas of Hanover and Dresden per year and records up to 3000 variables per crash. The project is supported by the Federal Highway Research Institute (BASt) and the German Association for Research in Automobile Technology (FAT). The approach and data sampling of GIDAS is described in Otte et al. [14].

III. RESULTS

Statistical Analyses

An overview of the GIDAS data is given in Table 1 including the number of cases, vehicles, injured people (driver / passenger) and injuries. This table includes the different levels of the GIDAS accident data structure: case level, vehicle level, person level and injury level. Four categories were built:

I: All

II: Seatbelt used; MAIS 0+

III: Seatbelt used; MAIS 2+ (including MAIS unknown)

IV: Seatbelt used; MAIS 2+ (including MAIS unknown); with thoracic and/or lumbar spine injuries

The most severe injury of person defines the maximum injury level (MAIS), nevertheless what body part it concerns. Thoracic and lumbar spine injuries were identified if the injury was located to one of the spine vertebrae.

TABLE 1 TARGET GROUP DEFINITION WITH FOUR CATEGORIES (CAR'S FIRST YEAR OF REGISTRATION IN 2000-2011)

	I All	II Seatbelt Used MAIS 0+	III Seatbelt Used MAIS 2+ and unknown	IV Seatbelt Used MAIS 2+ and unknown Thorax / Lumbar Injuries
Cases	4,289	3,799	307	45
Vehicles involved	8,844	7,887	603	160
Casualties	5,765	5,132	432	48
Driver	4,642	4,129	326	34
Front passenger	1,123	1,003	106	14
Coded injuries	9,468	8,291	1,861	88*

*only Thoracic and Lumbar Spine Injuries

In total 4,289 cases were selected including 8,844 vehicles, 5,765 injured persons and 9,468 coded injuries. Fig. 4 describes the target group in percentages for the cases and the occupants.

Based on the 5,765 occupants (injured people) the seatbelt wearing rate was 89% (5,132). Eight per cent of the occupants (432) had a MAIS level greater than two, when the seat belt was used. In the group of MAIS2+ occupants 48 persons (11%) suffered a thorax / lumbar spine injury.

That means in regard to the case the level in 1% of all cases a thoracic and/or lumbar spine injury occurred. But that means as well that if a MAIS 2+ injury does occur, then in 15% of the cases a thoracic and/or lumbar spine injury is included.

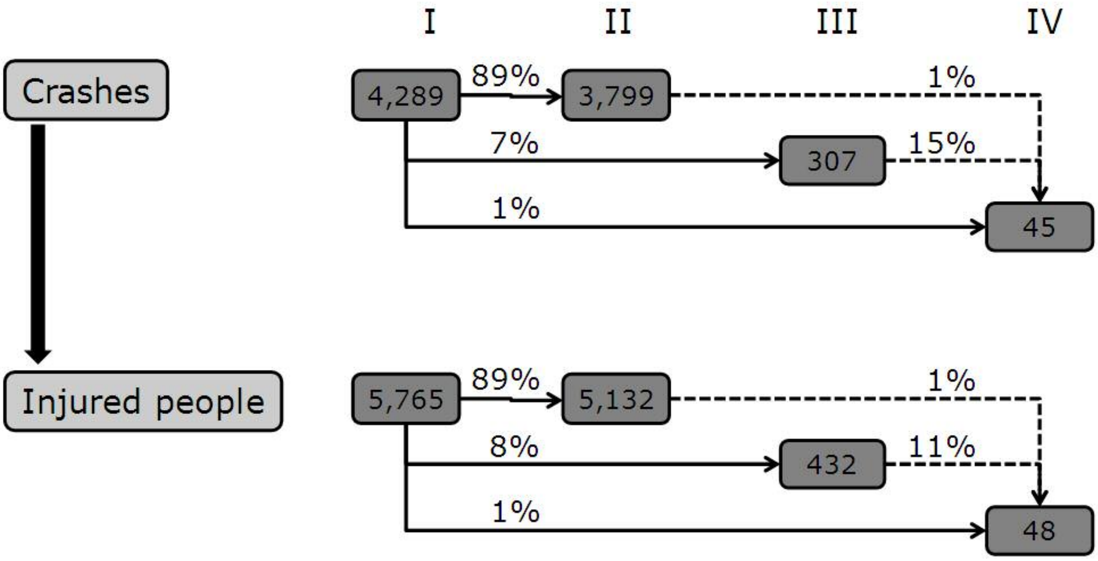

FIG. 4 TARGET GROUP DEFINITION IN PERCENTAGES FOR CRASHES AND INJURED PEOPLE

As a further step a detailed analysis into the injury level was conducted. All spinal injuries were considered in persons with MAIS greater than two (including unknown) and an AIS 2+ injury of the spine (including unknown). In total 100 injuries in the spinal region including the cervical area were identified. Fig. 5 shows the frequency and distribution of all spinal injuries in regard to their anatomical position. There were more than 20 cervical injuries with no further specificity in regard to the cervical vertebrae. These kinds of injuries are typically due to body motion and / or in combination with the airbag deployment. For the lumbar spine in total 45 injuries were recorded. There was no conspicuous lumbar spine vertebra identified because the occurrence is equally distributed. In general there were few injuries in the thoracic area compared to the neck and the lumbar spine.

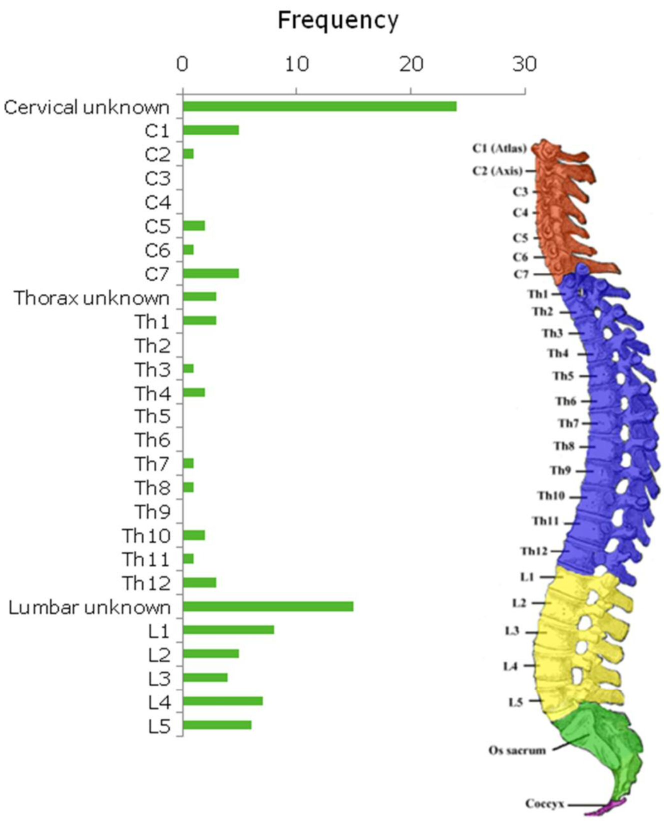

FIG. 5 RELATIVE FREQUENCY OF VERTEBRAE INJURIES ACCORDING TO THEIR ANATOMICAL POSITION

In Fig. 6 the type of spinal injury (left side) and the injury causation by spinal region (right side) is shown. In the thoracic and lumbar spine areas most injury types are fractures, whereas in the cervical area the injury type is either distortion or fracture. In GIDAS each injury is attributed with the injury causation by the survey team (right side Fig. 6). Most of the cervical injuries were assessed to be due to body motion whereas with the lumbar spine injuries, injury causation was much more difficult to assess; hence, 'body motion', 'backrest of front seat' and 'other' were allocated to lumbar spine injuries.

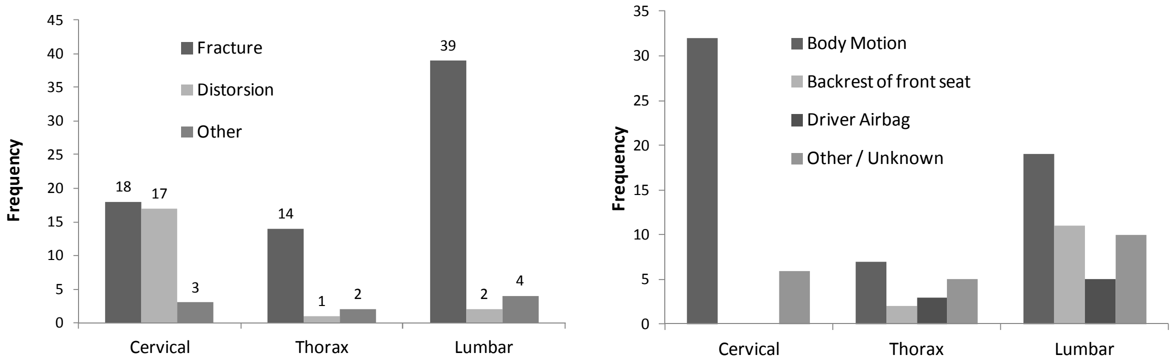

FIG. 6 LEFT: TYPE OF SPINAL INJURIES ACCORDING TO THE REGION; RIGHT: INJURY CAUSATION FOR THE SPINAL INJURY ACCORDING TO THE REGION

Case-by-Case Analyses

Based on the data query for the statistical analyses a selection for the case-by-case analysis was conducted. The 48 injured occupants from the category IV (seatbelt used, MAIS 2+ and injury to the thoracic and lumbar spine) were used for this step. These cases were reviewed in terms of the presence of restraint systems (presence and activation of seat belt pretensioner, load limiter, knee airbag, front airbag) in terms of accident severity (delta-v, EES, degree of overlap, intrusion), seat position (height, length), injury details and associated injury mechanisms. For the injury mechanisms a list of potential likely options was established and based on the data provided (pictures, medical report and reconstruction data) a selection made. The injury mechanisms are listed in Table 2.

TABLE 2 POSSIBLE INJURY MECHANISMS FOR THE THORACIC AND LUMBAR SPINE INJURIES

Submarining	Lateral components	Engagement of longitudinal beams[1]	Accident severity	Knee contact to dashboard	Moving objects behind the seat back	Other
Evidence for sliding under the lap belt	Lateral components in the occupant kinematics with significant influence in thoracic/lumbar spine injury	Assessment of deformation pattern with regard to the engagement[2] of longitudinal beams	subjectively assessed taking into account vehicle deformation, delta-v and EES	Knee had loading from impact to the dashboard	Objects flying against the seat back	none of the above items remark

The initially intended rating of OOP (evidence of Out of Position) as well as the rating of high lap belt forces was impossible based on the data, pictures and medical reports.

Thoracic spine AIS 2+ injuries were seldom found in the GIDAS data sample (11 cases). Most of the thoracic spine injuries (6 cases) were observed at the lower thorax (T10 – T12), however, there were also injuries at T1-T4 level (3 cases) and T7-T8 level (2 cases) reported. For the injuries at upper thoracic spine it is possible that they were caused by neck flexion. For the other thoracic spine injuries no suspicious circumstances were found.

[1] Longitudinal beams are the main rails in the front of the vehicle and a substantial part of the crash structure

[2] under/override phenomena, small overlap and centered pole impacts being considered as accidents with the potential risk of late restraint system triggering times

Following this assessment, the upper thoracic spine injuries were discarded for the case-by-case description and the injuries at the lower part (T10 – T12 level) were added to the lumbar spine injury analysis.

Lower spine AIS 2 + injuries in the data sample are all cases involving lumbar spine fractures including those fractures at lower thoracic spine (T10 – T12). This provided 21 cases for the case-by-case analysis. Lower spine fractures are distributed over the entire lower spine without any significant over or under representation, see Fig. 7.

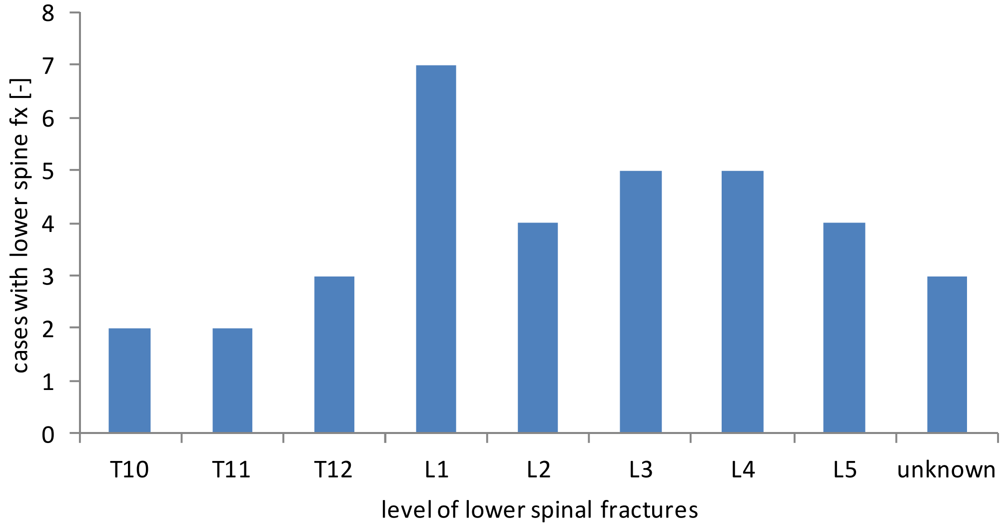

FIG. 7 DISTRIBUTION OF LOWER SPINE FRACTURES TO THE DIFFERENT VERTEBRA

Although most of the cases are associated with abdominal injuries (Fig. 8), there is no case with an evidence of submarining, see Fig. 9. For the analysis of abdominal injuries and submarining in conjunction with lower spine fractures, the two cases with fractures at lower thoracic spine without fractures at the lumbar spine were excluded. For both cases no abdominal injury was recorded.

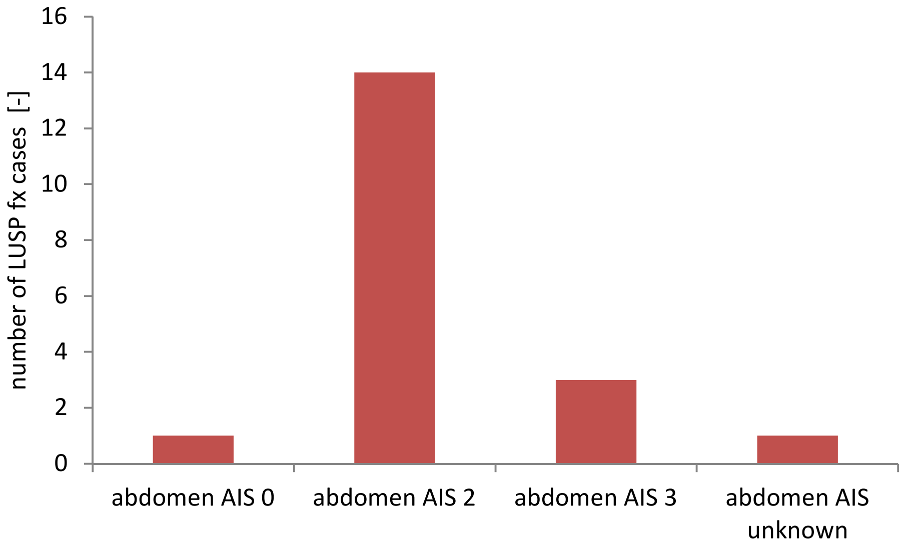

FIG. 8 LUMBAR SPINE FRACTURES AND ABDOMINAL INJURIES

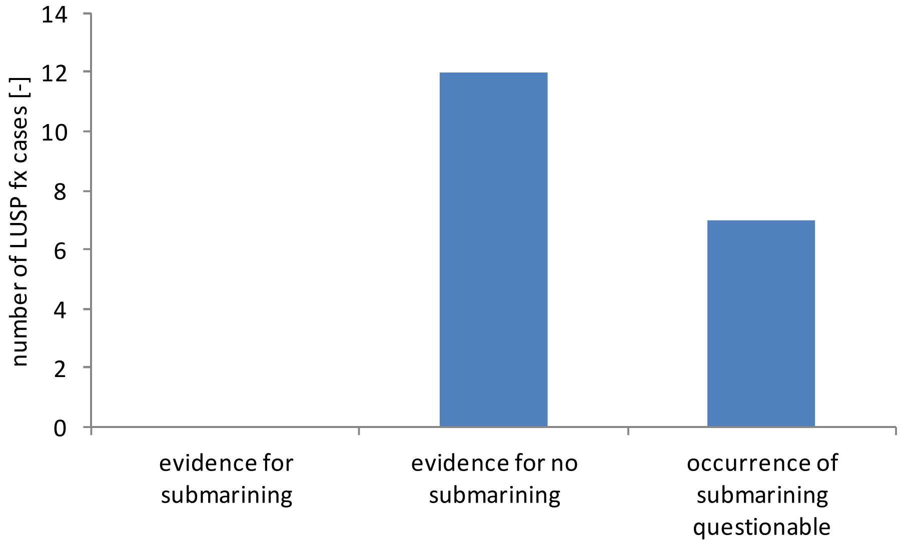

FIG. 9 LUMBAR SPINE FRACTURES AND SUBMARINING

Regarding seating position, seat adjustment in X and Z direction, age, gender, stature and weight, no clear correlations with spinal fractures were observed. The majority of cases are related to structural interaction issues (i.e., without involvement of the longitudinals following underriding / overriding, fork effect, small overlap) and that the majority of cases involve a considerable lateral component in the loads to the occupant (e.g., caused by overturn, lateral sweeping or rotation before, during or after the impact). Examples for cases without longitudinal engagement are given in Fig. 10.

small overlap | fork effect following central pole impact | override phenomenon

FIG. 10 EXAMPLES FOR CASES WITHOUT ENGAGEMENT OF LONGITUDINALS

In approximately 74% of the cases the longitudinals were not engaged (Fig. 11). In most of these cases the injury severity was MAIS 2 and the accident severity was rated subjectively as being low. For the cases with MAIS 3+ injury the accident severity was higher, mainly medium to high.

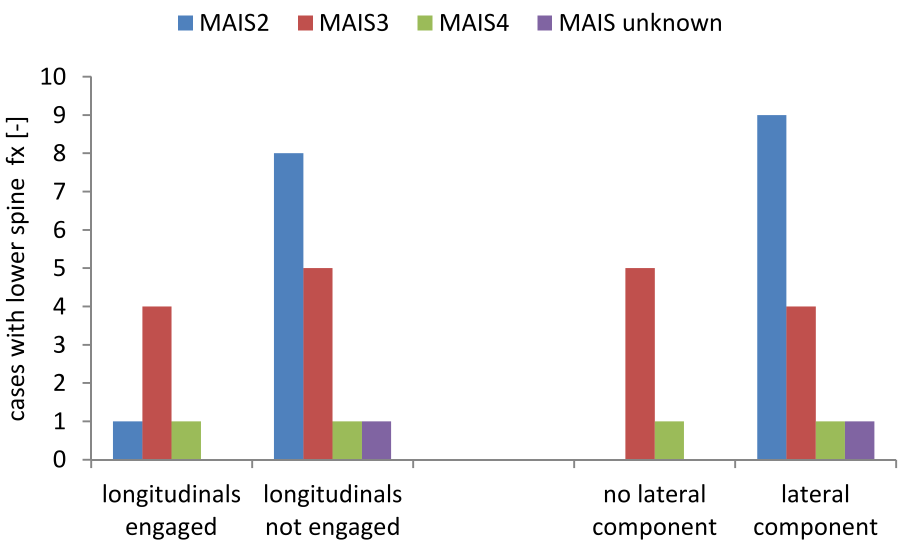

FIG. 11 LUMBAR SPINE FRACTURES DEPENDING ON LONGITUDINAL ENGAGEMENT AND LATERAL LOADING OF THE OCCUPANT

The other important observation is that in the majority of cases with lumbar spine fractures and MAIS 2+, lateral loading to the occupant was observed, see Fig. 11. The lateral loading was caused by rollover after impact, rotation after impact, a lateral component during impact and sweeping before impact.

One of the theories regarding the cause of lumbar spine injuries was that the restraint system characteristics may be responsible. In most of the cases seat belt pretensioners (mostly at the reel) were present. Only in a very few cases an additional pretensioner at the buckle or anchor was present, see Fig. 12. As the airbag was activated in most of the cases (19 of 21 cases), it can be concluded that the pretensioner also was. Load limiters were also present in these 19 of 21 cases.

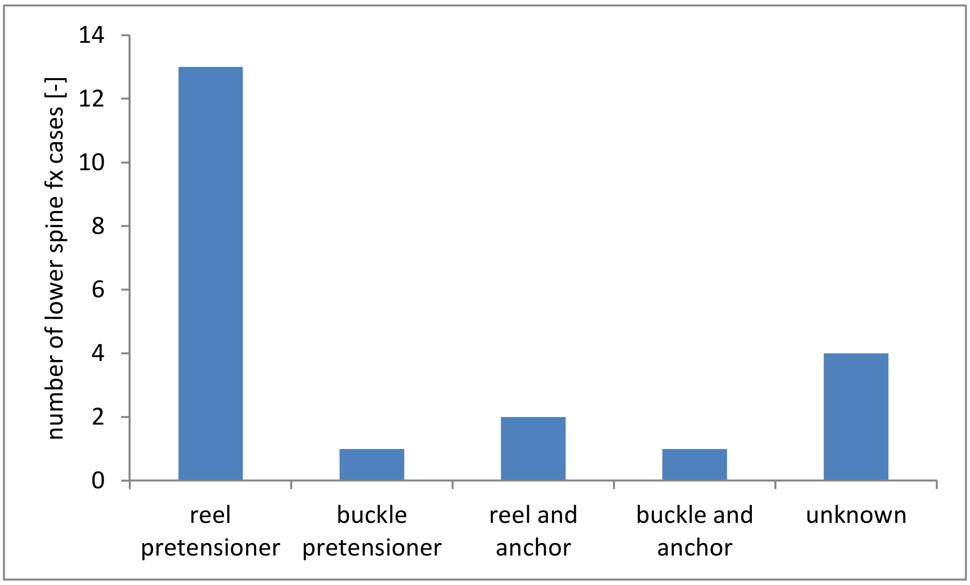

FIG. 12 PRETENSIONER LOCATION IN THE CASES WITH LOWER SPINE FRACTURE

There was no case with a knee bag installed at the position of the occupant with spinal injuries.

IV. Discussion

The strong passenger compartment and minimal intrusion, which have been strongly encouraged by UN Regulation 94 and Euro NCAP, are very important for safety. Also, the response of vehicle manufacturers and the restraint system suppliers have greatly reduced the risk of fatal injury to vehicle occupants in a frontal collision.

Although most of the lumbar spine fractures in the case-by-case analysis are associated with abdominal injuries, these are mainly rated as AIS2 injuries. This together with the individual case judgment as to whether or not submarining occurred does not support the hypothesis that the lumbar spine injuries in this data sample are likely to have been caused by the seat belt syndrome. In case of lumbar spine injuries caused by direct loading from the lap belt, higher abdominal injury severity levels would be expected.

In other studies, for example by Richards et al. [6] a correlation between belt geometry resulting in submarining and lumbar spine injures was postulated. This was supported by analysis of NASS accident data, which showed a correlation between the occurrence of abdominal and lumbar spine injuries. Furthermore, they tried to support this theory by frontal sled tests with the Hybrid III dummy in a nominal seating and belt position, which resulted in very low lumbar spine loadings. However, the investigated vehicle fleet might not have been equipped predominantly with pretensioners and optimised seat pans. In this study based on GIDAS data in nearly all cases where lumbar spine injuries were observed, the vehicle was equipped with a pretensioner, which was activated during the crash and should have minimized the risk of submarining. Therefore the injury mechanism was probably not related to the seat belt.

This theory is supported by the finding of Pintar et al. [15]. They found an increase in the incidence of thoracolumbar fractures in frontal impact crashes as a function of vehicle model year. They investigated thoracolumbar spine injuries based on NASS data in vehicles with model year from 1986 to 2008. Based on their analysis the occurrence of lumbar spine injuries increased in modern vehicles. The equipment rate of pretensioners increases in newer vehicles compared with older vehicles which also leads to a decrease of submarining risk. Based on this it can be concluded that in modern vehicles the increased risk of lumbar spine injuries is not related to direct loading by the seat belt. This statement is in line with the observation in the GIDAS study which shows that lumbar spine injuries occur without any evidence of submarining.

The benefit of three-point seat belt systems to reduce the severity of thoracic / lumbar spine injuries is also shown in a clinical retrospective study by Inamasu et al. [16]. They observed that compression/burst fractures still occur in properly restrained front seat occupants. They proposed that investigating the injury mechanism of axial loading fractures may be important to improve safety further for automobile occupants. High axial loadings to the thoracolumbar spine can be caused by severe occupant seat pan interaction as described above.

Occupant seat pan interaction in relation to the crash pulse is also an item of further research proposed by Pintar et al [15]. According to their analysis with NASS data the collision opponent seemed to have an influence on the level at which the spine was fractured, suggesting that the crash deceleration pulse may be influential in the type of compression vector that migrates up the spinal column. According to those authors, anti-submarining seat pans and stiffer vehicles might lead to increased forces introduced into the lumbar spine. They proposed further biomechanical research to investigate these factors.

In approximately 71% of the cases reviewed for the study, with fractures of the lower spine the longitudinals were not engaged with the majority of them being rated as accidents with low severity and low injury severity (MAIS 2). Edwards et al. [17] concluded in a similar GIDAS sample (frontal impact cases with UN Regulation 94 compliant vehicles) that in 12% of the cases structural interaction issues (under/override, fork effect, low overlap) occurred. That means that there is a noticeable difference in the accident situation when comparing all frontal impact accidents of ECE R94 compliant cars and cases with lower spine fractures. As the control study was conducted earlier, the observation period was shorter (2000 to 2010) and the study included fewer cases (2,862). However, the difference in the sampling period is small compared to the difference in the result. It is important to note that impacts where the designed load paths (e.g. longitudinal rails) are not engaged result generally in greater deformation length, a lower mean deceleration, but high peak acceleration at the end of the crash. It can be assumed that when the longitudinal beams are loaded then the energy of the collision is managed better by the vehicle crash structures. This allows the restraint system to perform in conditions closer to those in which it is likely to have been developed. Therefore, whilst the mean acceleration may be higher, the pulse more closely resembles that for which the system has been optimized. Furthermore it can be expected that the restraint system is triggered considerably later following the atypical acceleration pulse shape.

Comparable to the structural interaction issues, in approx. 71% of the cases with lower spine fracture a lateral component in the loading of the occupant was recorded. It is important to note that structural interaction issues and a lateral component of loading were often observed. The recorded observations regarding the combination or individual occurrence of these features is shown in Fig. 13. Unfortunately no control data were available to compare the occurrence of lateral components in the case-by-case analysis with a general data set.

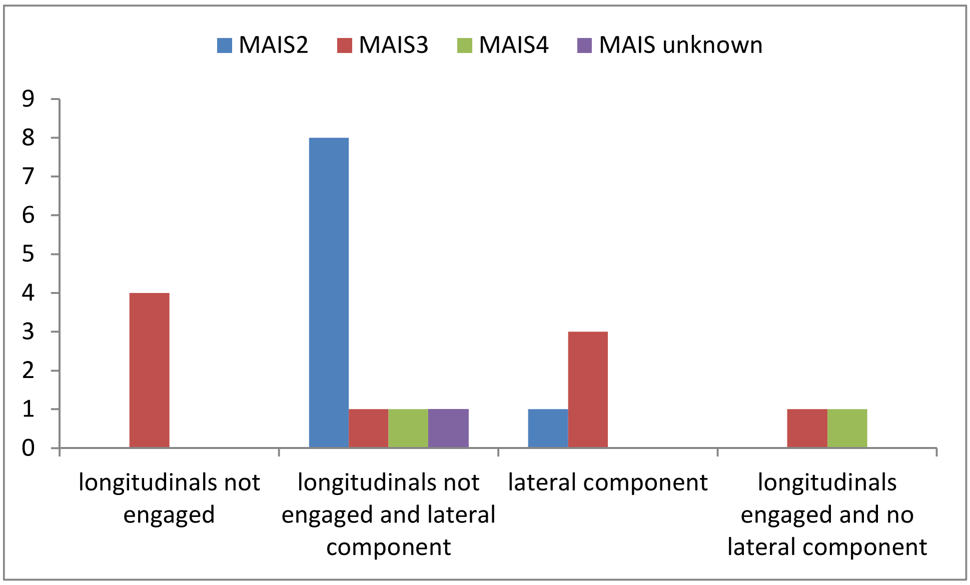

FIG. 13 ISOLATED AND COMBINED ACCIDENT PATTERN ENGAGEMENT OF LONGITUDINALS AND LATERAL COMPONENT

Although the majority of cases had a pretensioner at the reel, it is invalid to draw any conclusion from that. On the one hand, the position of the pretensioner in the accidents is highly influenced by the position of the pretensioner in the fleet. An analysis of the pretensioner position amongst 336 recent cars shows that in approx. 80% of the car models the pretensioner is located at the reel. This might change when including the registration numbers of the models in the analysis. On the other hand, the pretensioner might have limited influence on the dummy loading in the cases with late firing time, as expected in the cases with structural issues. In most cases, the occupant loading likely exceeds the force of the pretensioner.

To conclude the case-by-case analysis it can be noted that lower spine fractures either occur in severe accidents with other injuries being more severe than the lumbar spine injury or in accidents without the engagement of longitudinals and/or lateral loading to the occupant.

V. CONCLUSIONS

In this paper the spinal injury incidence was investigated with the analyses of road accident data. Statistical and case-by-case analyses were conducted with the focus on injuries to the lumbar and the lower thoracic region. For the analyses GIDAS data were used.

Although the overall safety in newer cars is increasing and the occupant compartment is usually stiff enough to prevent intrusion-related injuries, the acceleration pulse in an accident can be considerably high leading to acceleration-related injuries. Nevertheless, in frontal impacts without intrusions into the passenger compartment lumbar and thorax spine injuries, covering burst, compression or dislocation fractures as well as soft tissue injuries, were found.

In total 4,289 cases were selected including 8,844 vehicles, 5,765 injured persons and 9,468 coded injuries. If a MAIS 2+ injury does occur, then in 15% of the cases reviewed a thoracic and/or lumbar spine injury is included. Most of the injuries were fractures and occurred in the lumbar spine area. Lumbar spine fractures were distributed over the entire lumbar spine (L1 – L5) without any significant over or under representation.

From the case-by-case analysis it can be concluded that lumbar spine fractures do occur in accidents without the engagement of longitudinals and/or lateral loading to the occupant. This deformation pattern may lead to a deceleration pulse with a lower mean deceleration and high peak acceleration at the end of the crash. Although most of the cases are associated with abdominal injuries, there was no case with a clear evidence of submarining. Regarding seating position, seat adjustment in X and Z directions, age, gender, stature and weight, no suspicious observations were made.

Further research is needed to investigate if there is a connection between the seat belt pretensioner and the injury mechanism.

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