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ABSTRACT

The purpose of this research was to present and analyze a previously unreported mechanism of injury within the automotive crash environment - spinal burst or compression fractures due to a vertical force component. Spinal burst fractures are comminuted fractures of the vertebral body which are often associated with retropulsed bone fragments into the spinal. Compression fractures are less traumatic fractures of the vertebral body with minimal comminution. Both fracture types can have varying degrees of neurologic deficit. The mechanism of injury is hypothesized to be a high energy compressive load along the axis of the spine initiated through the buttocks and pelvis or through torso augmentation (inertial loading of the lumbar spine by the torso).

Four crashes are presented as evidence of this injury mechanism within the automotive crash environment: two in the United States and two in Germany. All crashes involved a vertical force component to the wheels of the vehicle and subsequently to the occupants. Injuries included burst or compression fractures of the lumbar spine (3 cases) and the thoracic spine (1 case) with varying degrees of neurologic deficit. Injured occupants were males and females of various age (mean 30.5 ± 8 years), size, and physical condition. The range of axial loads experienced by the occupants in two of the cases was estimated between 10 and 20 Gs.

INTRODUCTION

Spinal burst fractures are comminuted fractures of the vertebral body which are often associated with retropulsed bone fragments into the spinal canal (Figure 1). Compression fractures are less traumatic fractures of the vertebral body with minimal comminution. Both fracture types can have varying degrees of neurologic deficit. Neurologic deficit (i.e., in the worst case, paralysis) is a life altering condition with significant long-term healthcare and rehabilitation costs. The mechanism of injury for this kind of spinal fracture has been hypothesized as the result of a high energy compressive load along the axis of the spine. This type of injury has occurred during falls from varying heights [1-3], aircraft ejection [4-7], helicopter crashes [5], and snowmobile crashes [8]. The majority of these injuries (i.e., aircraft ejection, helicopter crashes, and snowmobile crashes) were induced by +Gz impact loads. By definition, a +Gz impact is a vertical load along the axis of the spine oriented from inferior to superior.

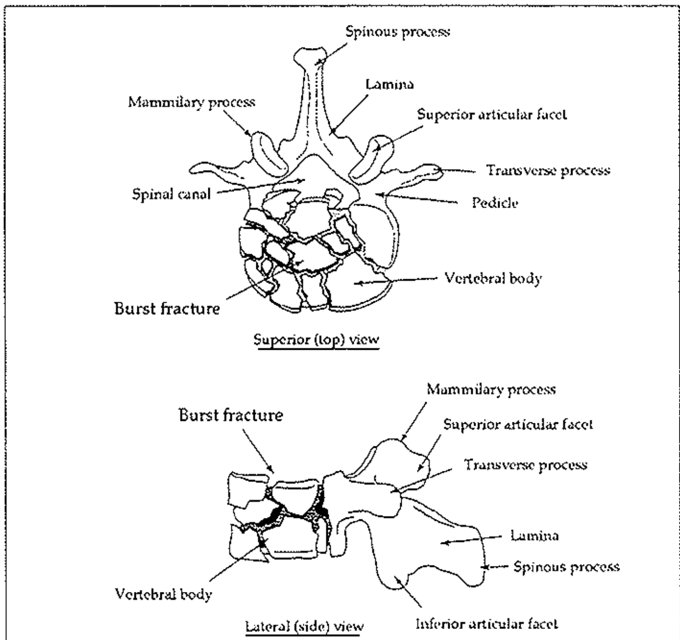

Figure 1: Comminuted Burst Fracture of a Lumbar Vertebra

There are two primary theories on the generation of axial compression necessary to induce spinal burst fractures; vertical impact transmitted through the pelvis and buttocks and torso augmentation. Torso augmentation is defined as inertial loading of the lumbar spine by the mass of the torso. Once the axial force is generated, fracture location and severity is governed by the impact strength of the vertebral bodies. In vitro compressive strength data of individual vertebral bodies [9-11] indicate that strength, as well as size, of human vertebral bodies increases inferiorly. Previous spinal impact research [12] indicates that strength (as measured statically) increases as strain rate increases (i.e., due to the viscoelastic properties of the vertebrae).

Axial impact loading of the human spine has been indicated in previous research on spinal fractures. Extensive ejection research was completed by the military in order to create safe and effective ejection systems which protect individuals from excessive compressive spinal forces during high velocity egress from military aircraft. The primary direction of force to the ejecting pilot was a +Gz vertical force.

King et al (1975) [13] completed human cadaveric testing utilizing a novel intervertebral load cell which was capable of measuring axial forces during vertical loading of the spine. Their results indicated that the human spine undergoes bending (due to the spine's posterior location within the body), as well as compression during axial loading. In addition, the articular facets were shown to play a significant role in distributing these forces. This finding supported the work of Ewing et al (1972) [14] which reported that pre-positioning aircraft pilots in extension prior to initiating the ejection sequence, increased the fracture tolerance of the spine by 20%. This research and others [4,15] provided significant tolerance data which led to incidence reducing modifications in military aircraft ejection systems.

Roberts et al (1971) [8] describes a similar +Gz spinal loading sustained during snowmobile crashes. Seven cases were presented in which lumbar and thoracic compression fractures were sustained during vertical impact to snowmobiles riders. Typically this vertical impact was generated by the vehicle traveling quickly over a bump. One of the compression fractures was sustained after a snowmobile suddenly dropped into a two foot depression obscured by snow.

Recently, this injury potential was indicated and analyzed through automotive seat testing [16]. The goal of this testing was to quantify dynamic overshoot in four current automotive seat designs. Dynamic overshoot was defined as the amplification of input +Gz acceleration as measured in an anthropomorphic test device (i.e., crash test dummy).

The purpose of this research was to present and analyze a previously unreported mechanism of injury within the automotive crash environment - spinal burst fractures due to a vertical force component. Support of this injury mechanism was established through case analyses of "real-world" automotive crashes in the United States and Germany. In addition, a discussion linking this injury mechanism to previous non-automotive injuries was completed.

MATERIALS AND METHODS

Four "real-world" automotive crashes in the United States and Germany involving vertical impacts to the vehicles were analyzed. Post-accident vehicle and crash site inspections were completed on all cases, as well as a detailed review of pertinent medical and police records. A literature search on non-automotive vertical impacts was also completed.

RESULTS

Vertical impact induced spinal burst or compression fractures were found in automotive crashes in which the vehicle left the road and experienced a vertical force. The vertical force was caused by the vehicle "bottoming out" in a ditch or during impact of the vehicle with the ground after dropping some height (i.e., +Gz impact). Once the vehicle's suspension bottomed out, the force was transmitted to the occupant via the vehicle frame and seat structure. It was this indirect impact to the occupant's buttocks (in the absence of any significant lateral force) that was hypothesized to cause fractures of the thoracolumbar spine.

Skeletal injuries included burst or compression fractures of the lumbar (3 cases) and thoracic (1 case) spine with varying degrees of neurologic deficit. Injured occupants included males and females of various age (mean 30.5 ± 8 years), size, and physical condition. The range of +Gz experienced by the occupants was estimated between 10 and 20 Gs in two of the cases. Standard military protocol for testing human subjects, indicates a transition from "safe" to "risk" zone for axial spinal tolerance at approximately 12 Gs [16]. This estimate does not account for reductions in spinal tolerance due to "out of position" loading (i.e., spinal loading eccentric to the long axis of the spine) which can occur during an automotive crash. Furthermore, single value tolerances do not account for variations in individual spinal fracture tolerance due to age, sex, size, and physical condition.

CASE HISTORIES - The following case summaries are from two crashes in the United States and two in Germany which involved automobiles sustaining vertical impacts through the wheels and suspension without significant lateral impact.

<u>Case 1</u> - On September 28, 1992, a 41 year old female was the 3-point restrained driver of a 1991 4-door Chevrolet Caprice. The driver slipped into a partial diabetic coma, ran a stop sign, and drove into a ditch where she struck a culvert (i.e., low ΔV frontal impact). During the event, the driver-side airbag deployed. As a result of driving into the ditch, the occupant moved

downward in her seat, compressing the seat cushion. Her downward movement was halted by the presence of a horizontal metal rod built into the seat. The force of hitting the rod was transmitted through the occupant's pelvis to her spine. The rod impact was supported by a slight deformation of the horizontal rod found during the post-accident vehicle inspection (Figure 2). The driver sustained a comminuted burst fracture of L1, involving both pedicles and retropulsion of bony fragments compromising the canal by greater than 50% with concomitant paralysis. In addition, she sustained a fracture of the right lamina of L1, angled into the postero-lateral thecal sac on the right causing compression. Input to the driver was estimated between 12 and 20 Gs [17]. A photograph indicating the damage to the exterior of the vehicle is contained in Figure 3.

Figure 2: Deformation of the Seat Structure Horizontal Rod (indicated by the arrows) in Case 1.

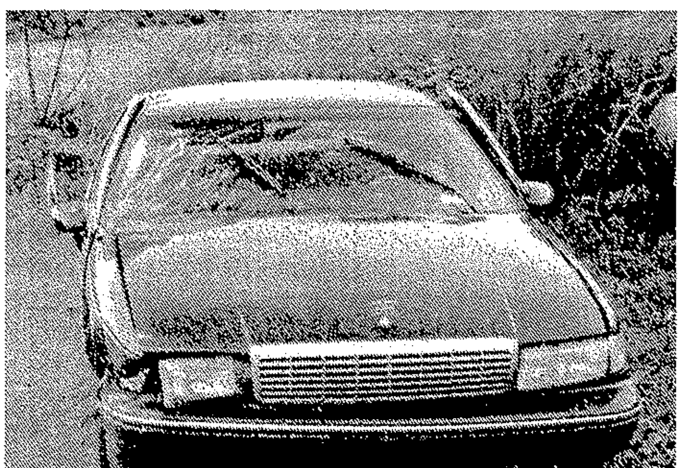

Figure 3: Post-Collision Photograph of Case 1 Vehicle.

Case 2 - On June 20, 1993, a male driver of a 1989 Nissan 240SX was struck by a white Toyota as it changed lanes. The driver lost control and hit the right hand side guardrail, spun back into the freeway and came to rest in the emergency lane. A 31 year old female was the rear seated occupant who sustained an L1 compression fracture with anterior wedging resulting in paraplegia. As the vehicle struck the guard rail, the right side of the car rode up onto the guard rail and stayed on the rail for some 12 - 24 meters [18]. The rear occupant flexed forward approximately 45 degrees and to her right during the initial impact with the guardrail. This orientation was supported by a clear head contact mark on the front seat back in front of her. The right side of the vehicle then fell to the ground from the guard rail. The ΔV of the frontal impact was estimated between 2.2 and 4.5 m/s with the +Gz impact to the rear occupant estimated between 10 and 20 Gs (Syson, 1995). A photograph indicating the damage to the exterior of the vehicle is contained in Figure 4.

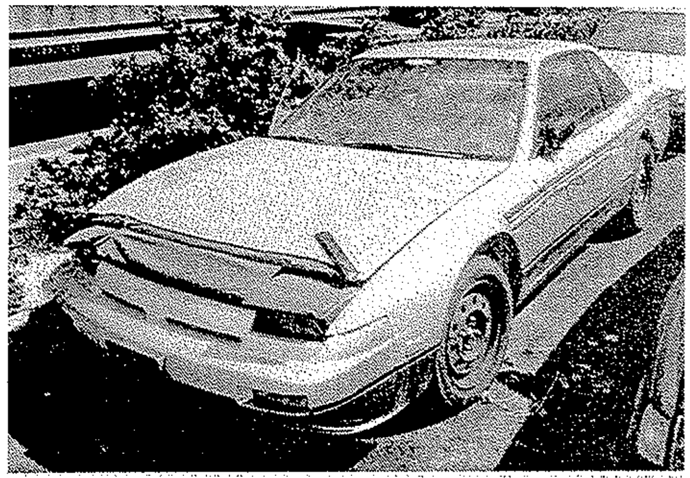

Figure 4: Post-Collision Photograph of Case 2 Vehicle.

Case 3 - On July 18, 1988, a 28 year old female driver, 3-point belted, in an airbag equipped Mercedes-Benz 260E (car line W124) left the road at the right side in a left turn, crossed a ditch, which caused the car to jump over a guardrail. After 50 m the car landed on its wheels in a flat hop cultivation. As the belt tensioner and the airbag did not deploy, it can be assumed that only a minor frontal force component acted on the driver. The injuries - compression fractures of the 5th and 6th thoracic vertebra without neurologic deficit - were caused by the vertical force and could not be prevented by the yielding seat structure, which is especially designed to absorb a reasonable amount of energy in the vertical direction (Figure 5).

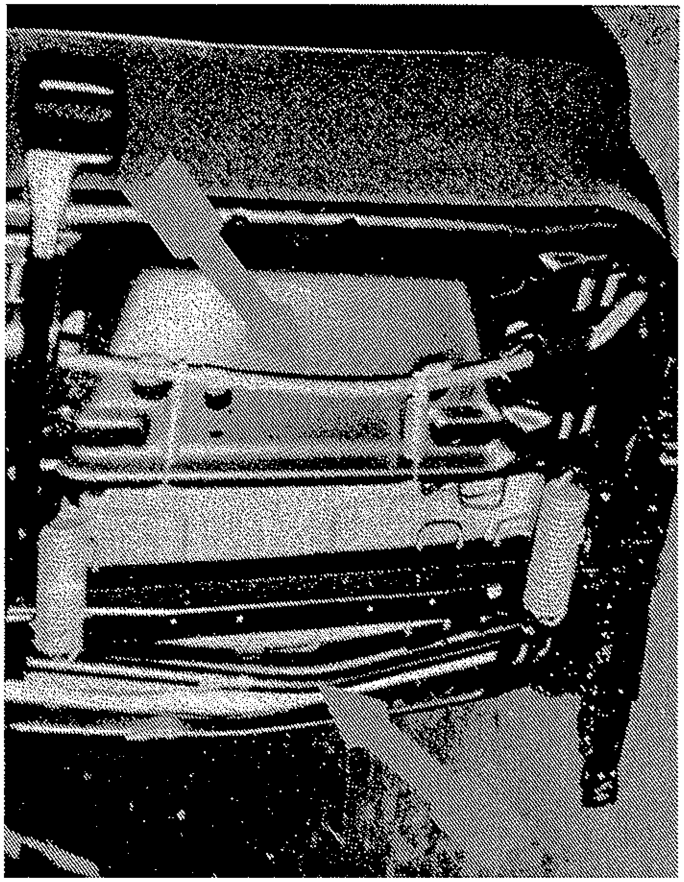

Figure 5: Photograph of Seat Structure Deformation in Case 3.

Case 4 - On November 7, 1991, a male 3-point belted driver at the age of 22 years in a Mercedes-Benz 190E 1.8 (car line W201) without an airbag installed, fell asleep and left the road at the right side in a left turn. Then the car went up a slight embankment; flew about 25 m through the air, landed on its wheels and flipped over. A photograph of the scene of the accident is contained in Figure 6. He suffered a compression fracture of the 2nd and 3rd lumbar vertebra. In this case the injuries of the spine were not only caused by a vertical force component, but also by at least a small frontal force component (evidenced by the activation of the belt tensioner). The seat structure (seat pan) was deformed by the vertical force (Figure 7).

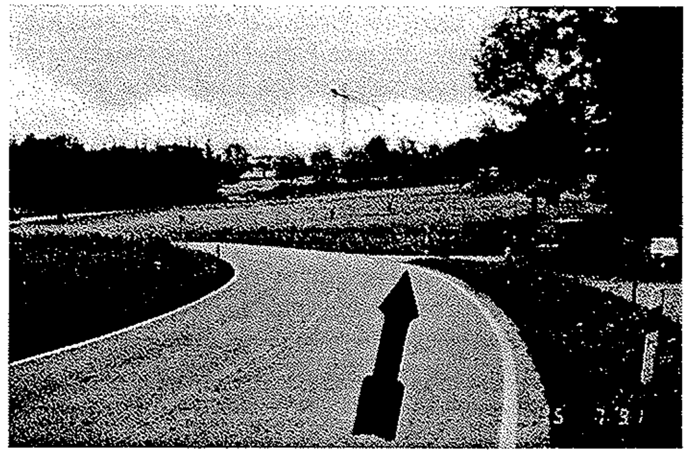

Figure 6: Photograph of Accident Scene in Case 4.

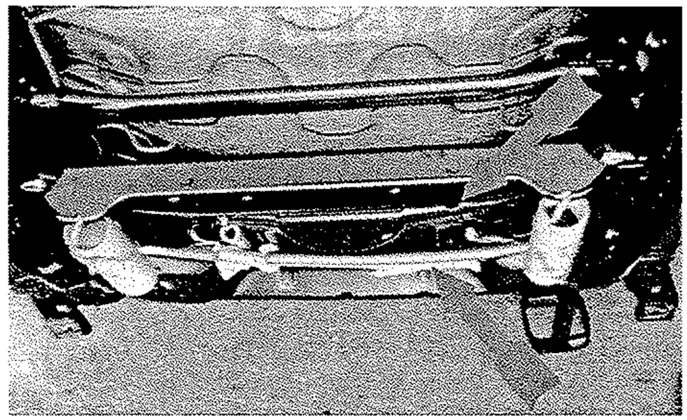

Figure 7: Photograph of Seat Pan Deformation in Case 4.

DISCUSSION

Spinal burst fractures within the automotive crash environment were indicated through case analyses of four automotive crashes in the United States and Germany. All crashes involved vertical impacts in the absence of any significant lateral impacts. Currently, the incidence of this injury mechanism in automotive crashes is rare, however, it was well documented in non-automotive vertical impact literature. Most prominent was the extensive military ejection research aimed at reducing spinal fractures during pilot ejection [4-7].

Kazarian (1977) [4] developed the following fracture classification during his research of the F/FB-111 escape module system:

- Posterior height compression fractures (hyperextension fractures)
- Anterior wedge compression fractures (hyperflexion fractures)
- Combined anterior wedge/posterior height compression fractures
- Burst injuries
- Lateral wedge compression fractures

The hyperextension injuries were caused during the powered inertia reel retraction portion of the ejection sequence. As the pilot was pulled into his seat, the backrest formed of fulcrum which forced the thoracic spine into extension, thereby causing the fracture. The hyperflexion injuries occurred during the impact of the escape module with the ground. The shoulder harness incorrectly allowed the pilot's upper torso to rotate excessively forward under the +Gz impact. The most frequently affected vertebral levels were T4-T7. The injury mechanism in the ejection sequence most similar to the mechanism seen in the automotive cases was the landing phase which led to hyperflexion injuries of the thoracic spine.

The military ejection research was not directly applicable to the automotive cases since the pilots involved were young healthy males with optimal spinal alignment during the ejection sequence. The fracture strength of isolated vertebral bodies has been well documented through in vitro biomechanical research data [9-11]. Results indicate that fracture strength and size increase inferiorly. These results are supported by the fact that inferior vertebrae must support increased forces due to the body mass above them. Bell et al (1967) [9] indicated that the fracture strength of human vertebrae decreased with age and the onset of osteoporosis. The young age of the military pilots and their optimal spinal position suggests a higher spinal tolerance than that of the typical automotive passenger. Vertebral level dependent fracture strength coupled with age and sex dependent factors suggests that spinal fracture during +Gz impacts within the automotive crash environment may be seen at lower vertebral levels than those reported in military ejections. This theory was supported by 3 of the 4 current automotive cases and other non-military injuries in the literature.

Roberts et al (1971) [8] presented seven cases of spinal compression fractures in snowmobile crashes involving a +Gz impact. These fractures were concentrated in the inferior thoracic and superior lumbar spine (primarily T12 and L1).

Victoria et al (1983) [5] indicated that during military helicopter crashes between 1970 and 1979 there was a higher incidence of lumbar fractures than thoracic fractures (46.6% and 33.9%, respectively). In the same report, fixed wing aircraft ejection injuries contained more thoracic fractures than lumbar fractures (47.6% and 22.6%, respectively) while non-ejection fixed wing aircraft injuries contained more lumbar fractures than thoracic fractures (52.2% and 25.4%, respectively). This may be due to the increased spinal tolerance reported by Ewing et al (1972) [14] with optimal spinal column alignment.

Finally, this injury mechanism was documented during falls from various heights [1-3]. In most cases, a +Gz impact could be isolated.

The documentation of spinal fractures sustained by individuals experiencing vertical impacts in the literature and the four automotive cases presented here, indicate a strong correlation between spinal burst fractures in the automotive crash environment and other vertical impact induced spinal fractures. Several contributing factors are indicated. Automotive issues include seat, restraint, and suspension design. Passenger issues included occupant position during impact, age, sex, size, and physical condition. Further investigation is indicated to determine if future advancements can significantly reduce the risk of this injury in the automotive crash environment.

CONCLUSION

Existence of a previously unreported mechanism of injury was presented and analyzed through "real-world" automotive crashes and current non-automotive vertical impact literature. Spinal burst fractures can occur during automobile crashes with vertical impacts. These case studies indicate that the vertical force component was indirectly expressed to the occupant's spine through the vehicle and seat structure ultimately causing fracture. The injuries were similar to burst and compression fractures reported in military ejection research [4-7], helicopter crashes [5], snowmobile crashes [8], and falls from varying heights [1-3].

To date, the incidence of this injury mechanism in the automotive crash environment is rare, but it has been documented in the United States and Germany. The following conclusions were drawn from an analysis of the four automotive crashes and the literature on spinal fractures induced by vertical impacts:

1. Evidence of spinal burst fractures induced by vertical impact with negligible lateral impact in the case analyses of "real-world" automotive crashes and the non-automotive vertical impact literature supports the existence of this injury mechanism in the automotive crash environment.
2. Several factors contribute to the occurrence of this injury mechanism. Automotive issues included seat, restraint, and suspension design. Passenger issues include occupant position during impact, age, sex, size, and physical condition.
3. Further investigation and/or experimental research is indicated in order to further elucidate this injury mechanism within the automotive crash environment.

ACKNOWLEDGMENTS

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