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Biomechanics of Side Impact Injuries: Evaluation of Seat Belt Restraint System, Occupant Kinematics and Injury Potential

Srirangam Kumaresan, Anthony Sances, Jr., Fred Carlin, Russell Frieder, Keith Friedman, David Renfroe

Abstract: **Side impact crashes are the second most severe motor vehicle accidents resulting in serious and fatal injuries. One of the occupant restraint systems in the vehicle is the three point lap/shoulder harness. However, the lap/shoulder restraint is not effective in a far-side crash (impact is opposite to the occupant location) since the occupant may slip out of the shoulder harness. The present comprehensive study was designed to delineate the biomechanics of far-side planar crashes. The first part of the study involves a car-to-car crash to study the crash dynamics and occupant kinematics; the second part involves an epidemiological analysis of NASS/CDS 1988-2003 database to study the distribution of serious injury; the third part includes the mathematical MADYMO analysis to study the occupant kinematics in detail; and the fourth part includes an in-depth analysis of a real world far-side accident to delineate the injury mechanism and occupant kinematics. Results indicate that the shoulder harness is ineffective in far-side crashes. The upper torso of the belted driver dummy slips out of the shoulder harness and interacted with the opposite vehicle interior such as the door panel. The unbelted occupants had a similar head injury severity pattern compared to belted occupants. The present study is another step to advance towards better understanding of the prevention, treatment and rehabilitation of side impact injuries.**

Key Words: Biomechanics, Injury, Trauma, Side Impact

I. INTRODUCTION

Motor vehicle crashes are a major cause of death and serious injuries. Approximately 41,000 people are killed and 250,000 people are seriously injured in motor vehicle accidents annually [1]. It is estimated that an annual economic cost of motor vehicle crashes in the past has reached over $150 billion. Side impact crashes are the second most severe motor vehicle accidents resulting in serious and fatal injuries [2]. An annual average of 1.3 million occupants are involved in side crashes out of 5.2 million total occupants, and approximately 33,000 occupants sustained fatal and serious injuries in side impacts.

One of the occupant protection systems in the vehicle is the three point lap/shoulder harness. The lap/shoulder harness restraints have been proven to reduce occupant movement inside the vehicle and provide ride down during frontal impacts [3]. Furthermore, it minimizes occupant ejection during lateral impacts. However, the lap/shoulder restraint is not effective in a far-side crash (impact is opposite to the occupant location) since the occupant may slip out of the shoulder harness. Numerous researchers have addressed the injury patterns of occupants in far-side impacts [4-11].

Augenstein, et al, studied the injury potential to occupants involved in far-side crashes by examining the database of National Automotive Sampling System (NASS) for the year from 1988 to 1998 [4]. Authors found that the contact with opposite side of the car interior was one of the most frequent causes of serious injury (Abbreviated Injury Scaling – AIS 3+) to the driver during the far-side crashes. Digges conducted vehicle to vehicle crash tests and examined the NASS database and found that the most harmful injury source was the opposite side of the car and found the shoulder belt ineffective [12]. Fildes studied the injury sustained by drivers in side crashes in Australia. [7]. The study found that the AIS 2+ head injury was twice as much in far-side crashes compared to near-side crashes. Frampton studied the injury patterns of restrained occupants in far-side crashes and found that the AIS 2+ injuries were higher in perpendicular crashes compared to oblique crashes [8]. Digges, et al, studied the injury patterns in the far-side crashes by examining the NASS database on front seat occupants with serious or fatal injuries and by simulating the finite element models [6]. The authors found that the head was the most frequently injured body region in far-side crashes. These studies have addressed some of the injury issues to occupants in far-side crashes. However, a comprehensive approach is lacking. Consequently, the present study was designed to conduct experimental car-to-car crash test analysis, epidemiological analysis, mathematical modeling and a detailed real world accident analysis.

II. MATERIALS AND METHODS

Part I (Experimental study): The first study involves a car-to-car test. The 1982 AMC Concord four door was impacted by a 1996 Crown Victoria four door. A belted 50% Hybrid III dummy was placed in the driver's seat of the AMC Concord and the seat belt restraint was equipped with an emergency locking retractor and cinching latch plate. The driver's seat was positioned at 1.5 inches (3.81 cm) forward of full rearward and at an angle of 20 degrees. The passenger seat was positioned at full rearward and at an angle of 20 degrees. The AMC Concord was impacted in the right front side. The Concord vehicle weighed about 3000 pounds and the Crown Victoria weighed about 4800

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The contact author is Srirangam Kumaresan at Phone; 805-685-5343; e-mail:kumar@engineering.ucsb.edu

pounds. The dummy had three Endevco 7264-2000 accelerometers in the head and an ATA Dynacube SN 288 block angular accelerometer. The triaxial accelerometers were attached close to the center of gravity. Two interior high speed 1,000 frames per second cameras and a video camera recorded the crash event. To simulate an intersection collision the Concord was crabbed at an angle to obtain the principal direction of force of 58 degrees with respect to Concord. The speed of the Crown Victoria prior to impact was 55 mph (88 km/hr). The vehicle was instrumented with accelerometers at the center of gravity. All data were sampled at 10 kilohertz. The accelerations were filtered at SAE class 1000 and the angular velocities at SAE class 180. The Head Injury Criteria (HIC) at 15 msec and 36 msec time intervals were calculated from the resultant tri-axial acceleration and the angular acceleration was derived from the angular rate sensor.

Figure 1: Position of the target vehicle (left) and bullet vehicle (right) prior to impact

Figure 2: Position of the belted dummy after impact

Part II (Epidemiological study): The second study involves the analysis of the injury database maintained by the National Highway Traffic Safety Administration (NHTSA). The database is called National Automotive Sampling System/Crashworthiness Data System database (NASS/CDS). The NASS/CDS is a stratified sample of light vehicles involved in highway crashed that were reported by the police. In this study, the NASS/CDS for the years 1988 to 2003 was evaluated to examine the serious head injury (AIS 3+) to belted and unbelted drivers involved in side crashes. The head injury patterns were examined for the accident severity of change in velocity of 20 to 30 miles per hour (32 to 48 kph) and more than 30 miles per hour (48 kph) with principal direction of force from 2 to 4 o'clock.

Part III (Mathematical Modeling study): The third part involves the mathematical simulation of crash using the MADYMO computer program [13]. The AMC Concord was modeled with ellipsoid surfaces attached to rigid bodies. The interaction between occupant and vehicle interior was modeled with appropriate force-deflection characteristics. The anthropometric dummy was used to simulate the driver. The seat belt restraint system was modeled using the finite element modeling approach. The Concord was subjected to a change in speed of 38 mph with a principal direction of force of 58 degrees (impact on the passenger side). The analysis was conducted until 280 msec. The 6th degree LaGrangian polynomial fit was used to define the input data pulse. The output included the Head Injury Criteria, angular acceleration, and linear acceleration.

Part IV (In-Depth Real World study): The fourth part involves an in-depth biomechanical analysis of real world accident involving the AMC Concord and the Crown Victoria. The belted driver of the AMC Concord in the real crash sustained serious head injury by impacting the passenger's side door panel. The vehicle was inspected and the medical records of the driver were analyzed to study the mechanism of injuries.

III. RESULTS AND DISCUSSION

Part I (Experimental study): The longitudinal change in speed of the AMC Concord was 14.5 mph (23.2 kph) and the lateral change in speed in Crown Victoria was 27.3 mph (43.7 kph). The resultant change in speed is approximately 31 mph (50 kph). The belted dummy in the vehicle measured the head injury potential. The resultant peak acceleration in the Crown Victoria was 35.3 G at 57 msec. The longitudinal change in speed of the Crown Victoria was 28.2 mph (45.12kph) and the lateral change in speed in Crown Victoria was 9.7 mph (15.5 kph). The resultant change in speed was approximately 30 mph (48 kph). The resultant peak acceleration in the Crown Victoria was 23.2 G.

The dummy in the AMC concord impacted the upper portion of the right door. The dummy's head angular acceleration was 14,386.5 rad/sec^2 at 133 msec. This value was above the injury tolerance of 4,500 rad/sec^2 proposed by Ommaya [14], of 4,500 rad/sec^2 proposed by Lowenheim [15], of 8000 rad/sec^2 proposed by Newman [16], and of 13,600 rad/sec^2 proposed by Pincemaille [17]. The peak head resultant acceleration was 137.2 at 132 msec while the head acceleration with 3 msec clip was approximately 100 Gs. The 3 ms clip head acceleration value of 100 G was above the 80 G injury limit proposed by Berg [18]. The Head Injury Criteria (HIC with 15 msec) was 635. The HIC was close to the tolerance value of 700. Other injury values such as angular acceleration and 3 msec head acceleration were above the injury values. The dummy's head impacted the passenger side door panel and measured higher injury values.

Augenstein, et al, studied the injury potential to occupants involved in far-side crashes by examining the database of National Automotive Sampling System (NASS) for the year from 1988 to 1998 [4]. Authors concluded that the head accounted for 40% of serious injury (AIS 3+) to the driver during the far-side crashes. Digges and Dalmatos also found similar findings of higher percentage of head injury in far-side occupants while analyzing the NASS database [12]. Digges and Dalmatos also conducted vehicle to vehicle crash tests with 60 degree crash vector and found that the shoulder belt was ineffective in preventing the head excursions. The dummy's head not impacted the door panel. The present study indicates that the dummy's head impacted the passenger door panel. The difference in the kinematic behavior is attributed to size of the vehicle, intrusion and restraint systems. Another issue in dummy kinematics is the entanglement of the seat belt with the upper extremity such as elbow and shoulder joints.

In a recent far-side crash study, Toomey, et al, have addressed the entanglement and injury potential to the partially restrained occupant by conducting three sled tests with dummies at a change of speed of approximately 22.5 mph (36 kph) and peak acceleration of 12.7 G. Authors concluded that the unrestrained seat belt entangled with the dummy's upper torso and significantly affected the kinematic response. Given the rigid upper extremity joints in the dummy and the difference between human tissue and dummy, the results should be carefully extended to real world accident analysis. For example, the rigid elbow joint of the dummy would easily entangle with the seat belt due to the cavity. It is well known that a significant difference in kinematic behavior exists between human cadaveric tissue and dummy in crash sled tests [19, 20]. Furthermore, many researchers have emphasized the limited far-side biofidelic nature of the Hybrid III dummy [12, 21]. The belt interaction force on the occupant depends on various parameters including, but not limited to, the position of the upper extremities, the crash severity, and the direction of crash force. A real world biomechanical analysis of occupant kinematic response such as ejection of belted occupants, showed no significant evidence of load marks on the occupant's body [22].

Part II (Epidemiological study): The NASS/CDS 1988-2003 data (Table 1) suggests that the probability of injury to the head region for the drivers is comparable in magnitude for belted and unbelted conditions. Our findings match with Digges, et al, who found a similar trend in the injury patterns for the head region of the driver with belted (42%) and unbelted (55%) conditions [6].

Table 1: Distribution of MAIS 3+ head injury to drivers in far side impacts (2 to 4 o'clock) in far-side crashes for belted and unbelted conditions.

	Belted	Unbelted
Delta V 20 to 30 mph	41%	59%
Delta V more than 30 mph	46%	54%

Part III (Mathematical Modeling study): The MADYMO computer simulation of the car-to-car crash quantified the head injury parameters of a belted driver under the conditions similar to experimental car-to-car crash. In general, the modeling output of high probability of head injury matches with the crash test output.

Table 2: Head injury values of belted driver in far-side crash

HIC – 36 msec	2,314
HIC – 15 msec	2,314
Angular acceleration (rad/sec2)	11,255 at 113 msec
Linear acceleration (G)	176 at 113 msec

Part IV (In-Depth Real World study): An in-depth analysis of a car accident involving a 1982 AMC Concord and 1996 Crown Victoria was conducted. The traveling speed of the AMC concord was approximately 19 mph and the traveling speed of the Crown Victoria was approximately 53 mph. The change in speed of the AMC Concord was 38 mph with a principal direction of force of 58 degrees (impact on the passenger side). After the impact, the AMC Concord rotated counterclockwise. The seat belted driver of the AMC Concord impacted the door panel and sustained severe head injury. The driver sustained the following injuries: right temporal skull fracture, right temporal epidural hematoma, bilateral intraventricular hemorrhage and midline shift to left (Figures 3 - 6). The swelling on the right side of the head from the parietal to temporal region indicates the stiff impact on the right side of the head with the vehicle interior. The inspection of the accident vehicle revealed a dent on the door panel of the passenger side indicating the head interaction with the door panel.

In summary, the present comprehensive study addresses the ineffectiveness of a shoulder harness in mitigating the serious injury during far-side crashes. Furthermore, similar injury severity is noted with unbelted occupants in these types of crashes. The current work is another step to advance towards better understanding of the prevention, treatment and rehabilitation of side impact injuries.

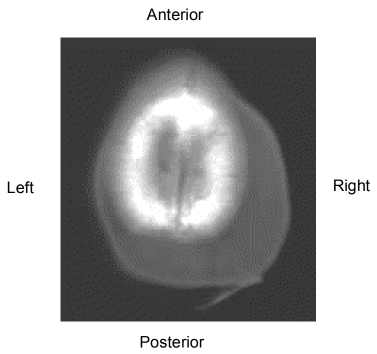

FIGURE 3: Axial CT Scan of head at vertex level showing the head swelling on posterior parietal area

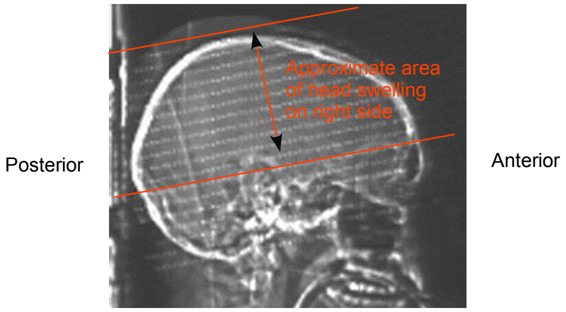

FIGURE 4: Scout view of CT head showing the head swelling from right parietal to temporal region

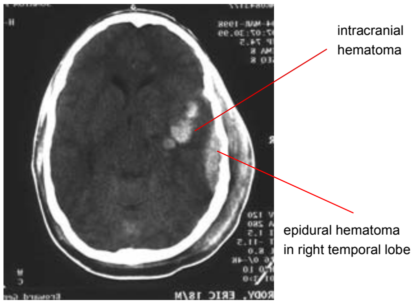

FIGURE 5: Axial CT scan image of head showing the brain injury – intracranial and epidural hematoma in temporal lobe

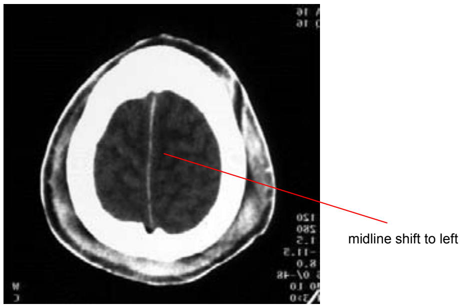

FIGURE 6: Axial CT scan image of head showing the brain injury (midline shift from right to left)

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