Comparison of Pelvis Injury Patterns and Loading Mechanisms in PMHS Tests and Real-World Side Impact Collisions

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ABSTRACT

Pelvis fractures can be complex and occur in many different regions of the bone. Loading due to side impact can transfer anteriorly through the pubic symphysis and posteriorly through the sacroiliac joint. Virtual testing with human body models (HBMs) has the potential to capture the complex loading mechanisms that contribute to pelvis fractures, but injury prediction with HBMs must be refined and validated using physical test data. Most postmortem human subject (PMHS) studies testing side impact and pelvic injuries use simplified test modes rather than simulating realistic boundary conditions. It is important to understand the differences between pelvis fractures resulting from in-lab tests and those sustained in real-world collisions, particularly for when these PMHS tests are used in injury risk function development to predict injuries caused by collisions in the real-world. This study seeks to compare injury types and loading mechanisms from existing PMHS tests to those observed in real-world side impact collisions from crash injury research and engineering network (CIREN) to examine their suitability for refining HBM injury prediction for the pelvis. 77% of PMHS tests with injuries had fractures in the anterior region of the pelvis, 23% in the iliac wing, 30% in the sacroiliac region, and 16% in the acetabulum, where a PMHS test could have fractures in multiple regions. Fractures were divided into primary and secondary side fractures, where the primary side was defined as the side impacted in a PMHS test and the side closest to the crash in a CIREN case. A higher proportion of cases with secondary side acetabulum and sacroiliac pelvis fractures was observed in CIREN compared to PMHS tests which may be related to interaction with structures in a vehicle environment. A pattern of "squeezing" the pelvis between the intruding door and the center console in near-side crashes was observed.

INTRODUCTION

Pelvis fracture is one of the most common types of injuries in side impacts (Samaha and Elliott, 2003). Figure 1 illustrates the prevalence of AIS 2+ pelvis injuries in nearside collisions. These injuries are particularly serious due to their proximity to major organs and arteries including the bladder, spleen, and internal and external iliac arteries. Fractures in the pelvic region can be considered unstable in cases when the integrity of the pelvic ring is compromised. These fractures can be difficult to recover from and create high injury costs for society (Hell et al., 1999).

Human pelvis tolerance and response to side impact have been tested by impacting postmortem human subject's (PMHS) pelvis with impactors and side walls. Many of these

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experiments use simplified impact environments including rigid impactors and frictionless seats to isolate the response of the pelvis. They provide meaningful data on pelvis tolerance and injury in lateral impact and have been used to create pelvis fracture injury risk functions (IRFs) for lateral loading (Peres et al., 2016).

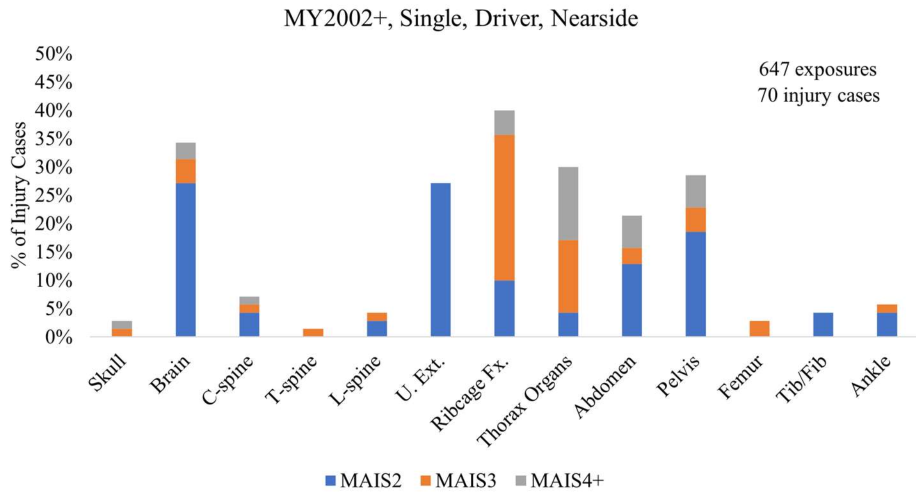

Figure 1: Distribution of AIS2+ injury types in single-event nearside collisions (PDOF 240-300 degrees), by injury severity (CISS collection years 2017-2022, belted driver, MY 2002+, unweighted).

While these tests are necessary and helpful, they differ greatly from real vehicle environments. Mainly, these experimental set ups typically do not include any vehicle-like structures that may influence pelvis injury in real-world crashes. Specifically for the pelvis, the vehicle seat interacts with the occupant in the seat cushion and the seat back. The intruding door and side airbag distribute the load to the pelvis compared to a localized load of an impact to the greater trochanter. Finally, the center console and interior structures of a vehicle can interact with the secondary side of the pelvis in a near side crash.

Previous studies on pelvis injuries in side impact cases used real-world crash data from crash injury research and engineering network (CIREN) to understand factors that affected pelvis fracture frequency (Tencer et al., 2005). Tencer et al. found that a center console in vehicles increased the frequency of bilateral pelvic fractures and pelvis injury in general when the door intrusion was greater than 15 cm. They concluded that the "trapping" of the pelvis occurs when the center console is rigid and loads the pelvis on the opposite side of the intruding door. This mechanism is thought to create additional forces on the far side of the pelvis that could be related to bilateral pelvic fractures seen in the field.

A multibody MADYMO model was used to calculate the primary and secondary loads of the intruding door and center console in near side impacts (Tencer et al., 2007). The parametric study showed that energy-absorbing structures rather than rigid center consoles can reduce the secondary peak acceleration in side impacts. They also found that allowing the seat to translate laterally during the impact reduced the primary peak acceleration.

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The objective of this study was to compare the pelvis injury patterns and loading mechanisms observed in experimental PMHS tests and real-world side impact collisions from CIREN. CIREN was selected as a tool to analyze real-world crashes due to its comprehensive information including crash metrics, medical imaging, and injury causation analysis as well as the multidisciplinary approach from medical professionals and biomechanical engineers. This analysis can be used to identify differences in boundary conditions and other factors that may be related to differences in fracture types and locations. It is important to understand not only if PMHS test injuries are representative of real-world injuries, but also if the injury risk functions we fit to predict PMHS test results will also predict real-life crash outcomes. The results from this study can help inform realistic boundary conditions for future PMHS tests that can be used in validation cases for HBMs and anthropomorphic test devices.

METHODS

PMHS test literature review

The literature was reviewed to identify PMHS test series that involved side impacts designed to study pelvis injuries. Each impact environment was assessed for modeling suitability considering PMHS weight, impactor speed and shape, and boundary condition details for future subject specific simulations with human body models. 204 side impact tests were compiled from 14 studies (Table 1). There were three main groups of load cases that included greater trochanter centered impacts, full side wall impacts, and far side simulated impacts. Far side simulated impacts were defined as tests where the PMHS moved into a stationary structure rather than the impactor or wall moving into the PMHS. Almost all the impact tests were performed using rigid structures with only a few tests including padding.

Roughly 78% of the PMHS tests selected from the literature were performed on male cadavers compared to 22% on female cadavers. The average age for the PMHS was 66. Out of the 204 tests, 74 (36%) were injurious resulting in a pelvis fracture. 12% of those injurious cases involved fractures to the secondary side of the pelvis that was not struck by the impactor or wall. Fractures were organized into four regions in the pelvis: the iliac wing, acetabulum, sacroiliac joint and sacrum, and the "anterior" region encompassing the superior pubic rami, inferior pubic rami, and pubic symphysis (Figure 2).

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Table 1: Previous biomechanical studies with lateral loading to PMHS.

Study	Load Case	N Tests	N PMHS
Ramet 1979	Impactor	7	2
Cesari 1982	Impactor	60	22
Nusholtz 1982,85	Impactor	7	7
Marcus 1983	Far side	8	8
Viano 1989	Impactor	14	8
Cavanaugh 1993	Far side	17	17
Bouquet 1994	Impactor	14	7
Bouquet 1998	Impactor	11	11
Kuppa 2003	Far side	20	20
Leport 2007	Impactor	16	8
Lessley 2010	Far side	3	3
Petit 2015	Wall	9	9
Lebarbé 2016	Wall	12	12
Petit 2019	Far side	6	6

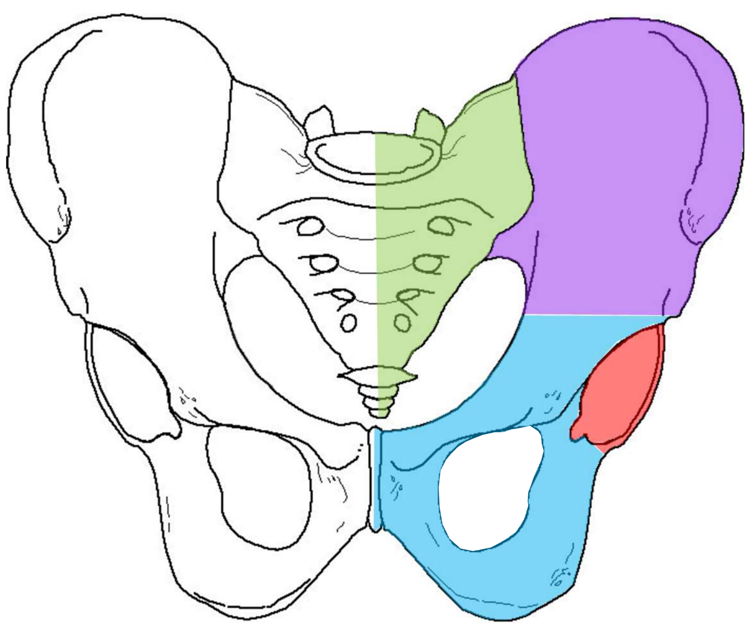

Figure 2: Regions of the pelvis: iliac wing (purple), acetabulum (red), sacroiliac joint (green), and anterior (blue).

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CIREN case review

185 CIREN cases with pelvis injuries were collected from 2017-2025. The original list was filtered into 34 cases that included side impacts, belted occupants, and available imaging and injury data. Side impact was defined as having a principal direction of force (PDOF) between 60 and 120 degrees, or 240 and 300 degrees, to account for near-side and far-side crashes. Each CIREN case was reviewed for pelvis fractures and injury patterns. There were 30 cases (88%) that involved drivers. 23 cases (68%) involved female occupants, and 11 cases (32%) involved male occupants. The average age for CIREN case occupants was 50. The mean BMI was 26 with 7 cases involving obese occupants having a BMI of 30 or higher (Figure 3). The pelvis was divided into the same four regions of interest as the PMHS tests described above.

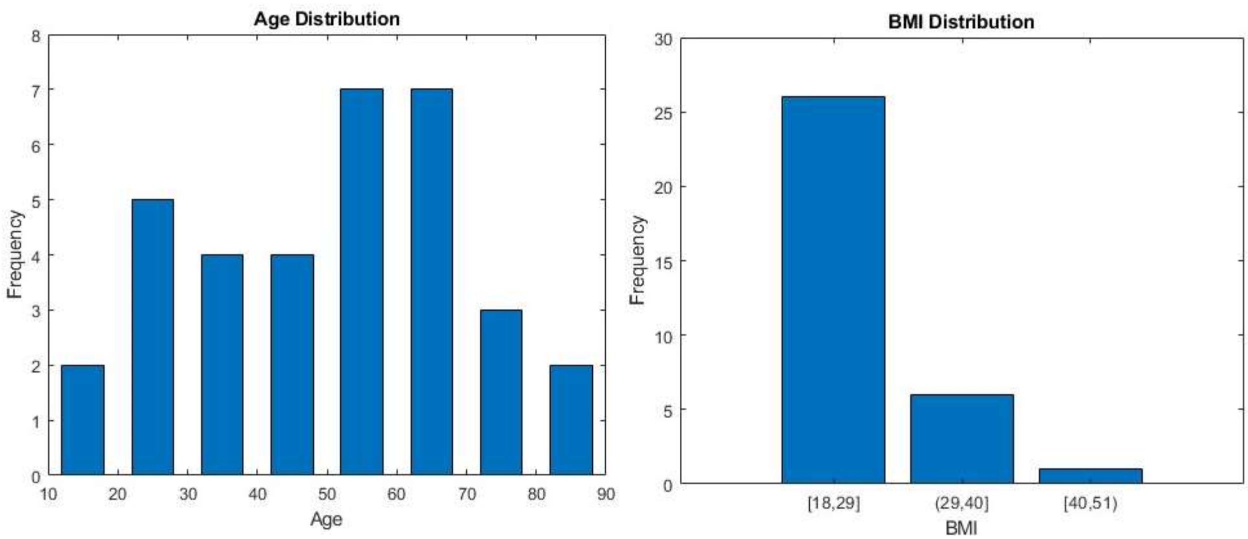

Figure 3: Distribution of occupants without different age groups (left) and BMI groups (right).

In the current analysis, near side crashes with "far side boundaries" were defined as crashes where the vehicle had an internal structure such as a center console or parking brake that could interact with the secondary side of the pelvis. Far side crashes and all other near side crashes without these structures were considered as impacts with no "far side boundary", meaning no internal structure could contact the secondary side of the pelvis. The distinction of boundary or no boundary was made using vehicle images and up to the author's judgement.

RESULTS

Anterior fractures were the most common with 77% of PMHS tests with injury descriptions provided having fractures in this region. Sacroiliac and iliac wing were the next most common with 30% and 23% respectively. Acetabulum fractures were less common in these impacts with only 13 occurrences or 16% of injurious tests.

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Only 12% of PMHS tests with any pelvis injury had fractures that occurred in the secondary side of the pelvis. In all PMHS load cases, the secondary side of the pelvis was free from contact with any far side boundary condition and did not interact with any structure that caused injury. Looking specifically at the injuries to the secondary side of the pelvis that has not been impacted by the impactor or side wall, we can divide the pelvis into the four regions of interest again. Seven tests (12% of injurious tests) had fractures in the anterior region of the secondary side of the pelvis. There were no fractures in the secondary side acetabulum or iliac wing, and five impacts (8%) resulted in fractures to the sacroiliac joint on this side.

Because of the nature of the CIREN query, all 34 side impact cases resulted in pelvis fracture. There were 6 far-side crashes and 28 near-side crashes. Diving the pelvis into the same regions of interest, 82% of cases resulted in fractures to the anterior region, 24% in the iliac wing, 35% in the acetabulum, and 74% in the sacroiliac joint.

After dividing the CIREN cases into vehicles with a far side boundary and without a far side boundary, there were 22 cases with this boundary and 12 cases without. Figure 4 shows an exemplary vehicle that contains a center console that could interact with the secondary side of the pelvis in a near side crash for the driver. Figure 5 shows an exemplary vehicle that does not contain this boundary and has minimal structures that could interact with the secondary side of the pelvis from the lateral direction. The center console is much lower than the one in Figure 4, so even when the intruding door pushes the pelvis laterally, there is less of a structure for the occupant to interact with. Looking at the four fracture regions again, 64% of CIREN cases with a far side boundary had fractures at the secondary side anterior region, 5% at the secondary side acetabulum, and 27% at the secondary side sacroiliac joint. For the CIREN cases with no far side boundary condition, 58% fractured at the secondary side anterior region and 17% at the secondary side sacroiliac joint. There were no secondary side acetabulum fractures for cases with no far side boundary, and there were no secondary side wing fractures in either scenario. Table 2 displays the comparison of injury proportions in these two vehicle categories.

Figure 4: Example of a vehicle with a far side boundary from CIREN case #276

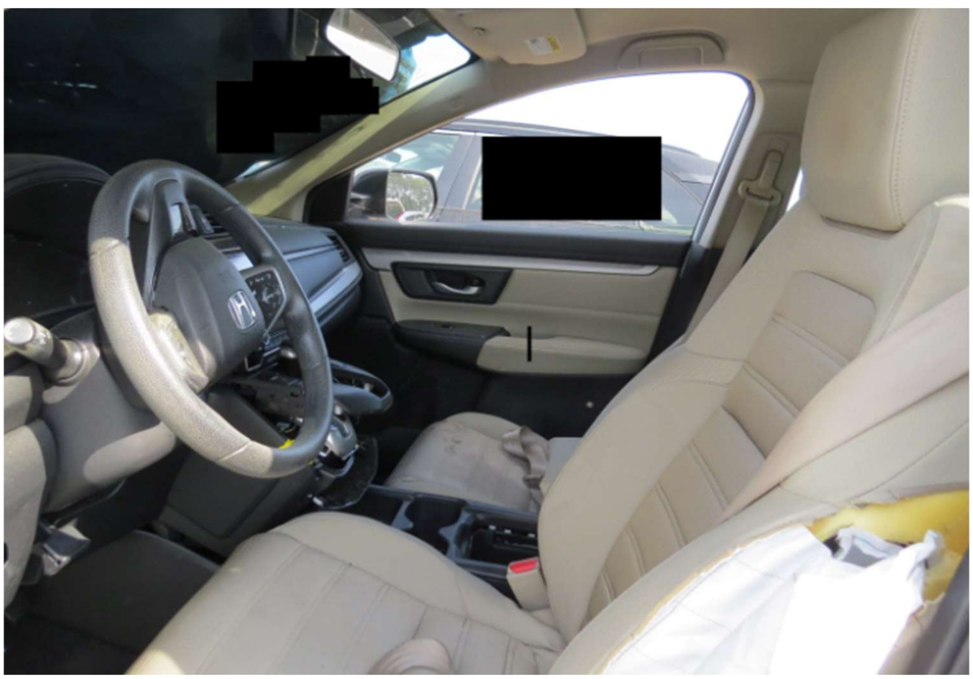

Figure 5: Example of a vehicle without a far side boundary from CIREN case #980035

Table 2: Breakdown of pelvis injury location in CIREN cases with and without far side boundaries

Secondary Side Region	Far Side Boundary (%)	No Far Side Boundary (%)
Anterior	64	58
Acetabulum	5	0
Sacroiliac	27	17
Iliac Wing	0	0

From the 28 near side crashes from CIREN, 14 (50%) of the occupant's injuries were most likely caused by squeezing the pelvis between the intruding door and the center console or other secondary side boundary conditions. In these cases, the intrusion from the side door caused a loss of space in the occupant compartment which pushed the occupant into the boundary on the secondary side. The intruding door alone was the main cause of pelvis injury for 12 occupants, and two cases had injuries attributed to osteopenia or osteoporosis (poor bone quality). Of the near side CIREN cases where secondary side pelvis fractures occurred, 78% had pelvic interaction with the center console or other structure in the inboard area of the vehicle that was noted to have caused injury.

DISCUSSION

The goal of this study was to identify and analyze injury patterns in PMHS tests and real-world CIREN cases of side impacts. The main side impact related differences in boundary conditions between simplified in-lab experiments and real-world crashes are the far side structures like the center console, the seat pan and back, and the distributed load from the intruding door or side airbag. While in-lab experiments provide a good reference for pelvic tolerance and response to lateral load, it is worthwhile to assess their representation of the injury mechanisms that occur in a real vehicle.

The experiments assessed in this study impacted the pelvis laterally using simplified boundary conditions like a linear impactor or side wall. In a real vehicle environment, the shape of the center console in a far side crash and intruding door or airbag in a near side crash create alternative load paths that may transfer forces differently throughout the pelvis. Because of the complex nature and shape of the human pelvis, the lateral load can be transferred anteriorly through the pubic rami, acetabulum, and pubic symphysis and posteriorly through the iliac wing and sacroiliac joint.

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Overall, in the CIREN cases, there were more acetabulum and sacroiliac fractures compared to the PMHS tests. 35% of CIREN cases resulted in an acetabulum fracture versus 16% in injurious PMHS tests. 74% of CIREN cases resulted in a sacroiliac fracture versus 30% in injurious PMHS tests. The injuries to these regions in the CIREN cases were thought to be caused by lateral impact, not interaction with the instrument panel or other frontal restraints.

When looking at the CIREN cases that had far side boundaries compared to those without, there was an increase in cases with fractures to all secondary side regions of the pelvis excluding the secondary side iliac wing which was not injured in any of the CIREN cases. In cases with a far side boundary, 64% had fractures to the secondary side anterior region compared to 58% of cases with no far side boundary and 27% had fractures to the secondary side sacroiliac joint compared to 17% of cases with no far side boundary. While an increase was observed, it was not vastly different considering the low number of cases in each category. It is important to note that the distinction between cases with and without far side boundaries was subjective to the authors' opinion and could be exclusive of other relevant structures in the vehicle. Prior studies found that occupants in vehicles with a center console were more likely to have a pelvis injury when there was at least 15 cm of door intrusion in a near-side crash (Tencer et al. 2005). They also found that bilateral pelvis fractures were more common in vehicles with center consoles. In the current study, all CIREN cases resulted in pelvis fractures, and bilateral pelvis fractures were common with 67% of cases involving fractures to both sides of the pelvis. The comparison of fractures in cases with and without far side boundaries can be visualized in Figure 6, where the radius of the circle in each region increases as the proportion of cases with fractures increases.

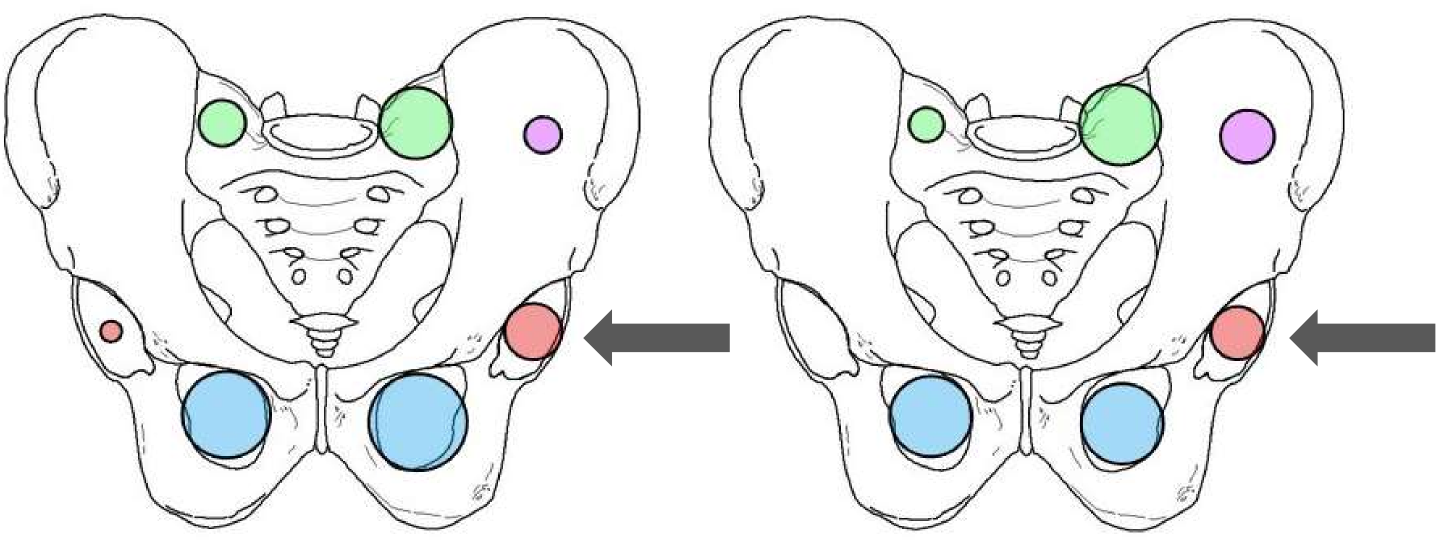

Figure 6: CIREN cases with far side boundaries (left) vs. CIREN cases without far side boundaries (right) where the arrow depicts the direction of primary impact, and the radius of the circle depicts the proportion of pelvis injury cases that had a fracture in that region.

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Comparing secondary side fractures occurring in PMHS tests to those occurring in all the CIREN cases, there is an overall increase in the proportion of impacts with anterior, acetabular and sacroiliac joint fractures. This could be caused by interaction with other structures in the vehicle. The secondary side fractures in the PMHS tests were most likely due to a combination of inertial load due to the original impact and a transfer of forces through the sacroiliac joints or pubic symphysis. The transfer of forces may be greater for subjects with osteoporosis, osteopenia, or weaker bone in general. This bone quality may correlate with older subjects (Oberkircher, 2018). The increase in secondary side fractures in the CIREN cases shows a potential difference in the injury patterns observed in the PMHS tests and the real-world cases that may not be accounted for solely by the center console. The comparison of PMHS test and CIREN case fracture locations and proportions can be found in Figure 7.

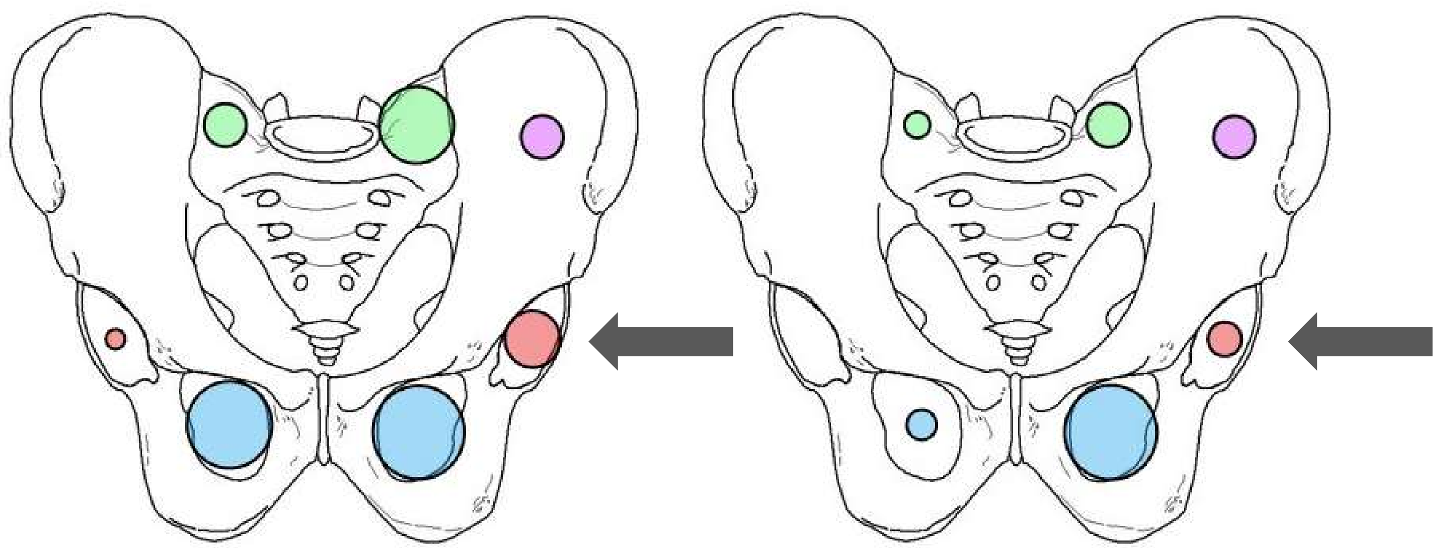

Figure 7: All CIREN cases (left) vs. injurious PMHS tests (right) where the arrow depicts the direction of primary impact, and the radius of the circle depicts the proportion of pelvis injury cases that had a fracture in that region.

To illustrate this observation, specific CIREN cases and PMHS impact tests that involved subjects of similar anthropometries were compared. Cesari et al. performed lateral impact tests centered on the greater trochanter with a rigid, rounded impactor, a rigid frictionless seat, and no far side boundary (Cesari, 1980 and 1982). Run N7 was a right-side impact performed on a 54-year-old male that was 184 cm tall and 84.2 kg with a BMI of 24.9. The speed of the impact was 41.1 km/h. The subject sustained pelvis fractures in the right iliac wing, right superior and inferior pubic rami, and the right sacroiliac joint. CIREN case number 3-C5-2020-091 (CIRENID: 646) was a near side crash for the left front driver, a 55-year-old male that was 185 cm tall and 77 kg with a BMI of 22.5. The delta velocity in this crash was 44 km/h. The occupant sustained pelvis fractures in the left superior pubic rami, right superior and inferior pubic rami, right iliac wing, right sacroiliac joint, and the sacrum bone. The injuries were thought to be caused by a combination of door intrusion and impact with the seat belt buckle and wide, high center console. Compared to

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the PMHS test described, the pelvis injuries in this CIREN case were bilateral and attributed to forces on the secondary side of the pelvis rather than solely on the primary, impacted side.

Run D2 from Cesari et al. was a right-side impact performed on a 63-year-old female that was 160 cm tall and 53 kg with a BMI of 20.7. The speed of the impact was 30.8 km/h. The subject sustained pelvis fractures in the right iliac wing, right superior and inferior pubic rami, and the right sacroiliac joint. CIREN case number 3-C4-2020-150 (CIRENID: 542) was a near side crash for the left front driver, a 25-year-old female that was 170 cm tall and 52 kg with a BMI of 18. The delta velocity was 36 km/h. She sustained pelvis fractures in the left superior and inferior pubic rami, left iliac wing, left acetabulum, as well as the right superior and inferior pubic rami and the sacrum bone. Again, the pelvis injuries in this CIREN case were bilateral and could be related to the internal vehicle structures on the secondary side of the pelvis that restrict the occupant from moving away from the intruding door and "squeeze" the pelvis in a side impact.

While these specific case comparisons do not represent the entire population and are not a one-to-one comparison, they provide some specific context for how occupants in real-world crashes can experience vastly different interactions than the PMHS in the impactor tests from the literature. The vehicle structures like center consoles, parking brakes, and belt buckles that interact with the pelvis may contribute to the probability of pelvis fractures in side impacts, especially cases where the door intrusion causes a loss of space in the occupant compartment and squeezes the pelvis. This mechanism may also contribute to the probability of bilateral pelvis fractures and specifically pelvis fractures to the secondary side of the pelvis that is not impacted by the intrusion.

There were many limitations and assumptions in this study. The CIREN database and this CIREN case subset are not representative of the population. These cases provide examples of side impact collisions that occur in the field, but conclusions cannot be made for the entire population of vehicle occupants. For the purposes of this study, no analysis was conducted on the crash energy or severity. Delta velocity was the only measure available for crash severity. This measure is not a good comparison to impact velocity in PMHS tests, as it is not equivalent to the impact velocity of the vehicle door or airbag in near side collisions or the center console in far side collisions. Lastly, the fracture descriptions in both PMHS tests and the CIREN database did not consistently contain detailed descriptions of the locations or severities.

This research is part of an ongoing project to develop IRFs for the THUMS and SAFER HBMs to predict pelvis fractures in side impacts. The PMHS literature review will be used to create load case environments for modeling, and the injury outcomes from the tests will provide data points for the IRFs. It is important to verify if the resulting IRFs can predict the effect of real-vehicle boundary conditions and possible "squeezing" mechanisms. The comparison of existing PMHS tests and real-world collisions can help inform how future side impact PMHS tests can be improved and expanded upon to represent boundary conditions that occupants experience on the road.

CONCLUSIONS

This study compared pelvis fracture patterns in PMHS tests and real-world side impacts. Pelvis fracture in side impacts remain a common and dangerous injury. While research has been conducted to improve occupant protection and review pelvis injuries in side impacts, the injuries resulting from experimental tests and field crashes should also be compared. Overall, a higher proportion of fractures on the secondary side of the pelvis was observed in CIREN cases compared to in-lab PMHS tests. A higher proportion of acetabulum and sacroiliac fractures was also observed. Comparison between fractures in experimental cases and real-world scenarios provides a meaningful look into how in-lab boundary conditions affect representation of real-world outcomes.

ACKNOWLEDGEMENTS

This work was funded by Autoliv Development AB and the THUMS User Community (TUC). The authors acknowledge Dr. Rodney Rudd of the National Highway Traffic Safety Administration (NHTSA) for his assistance in querying the Crash Injury Research and Engineering Network (CIREN) database. The opinions expressed here are solely those of the authors.

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