Development of Pelvis Injury Risk Curves for Iliac Bone Fracture Due to Lap Belt Loading in Female PMHS Sled Tests

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ABSTRACT – This study aimed to develop injury tolerance metrics for iliac bone fractures resulting from lap belt loading in frontal impact scenarios. We conducted 27 whole-body postmortem human subject (PMHS) sled tests with female specimens under various boundary conditions, including two crash pulses (32 kph and 50 kph), two seatback angles (22° and 45°), and three seat types (stiffer seat, soft seat, and stiffer seat with knee bolster). Out of 27 tests, 13 resulted in pelvic fracture, in which 9 showed at least one iliac wing fracture, predominantly in the left (outboard) position. Using Weibull distribution for survival analysis, we developed Pelvis Injury Risk Curves (PV-IRCs) for the small female cohort (N=18) and all-female cohort (N=27). At a 50% injury probability level, the mean lap belt force values were estimated at 5.5 kN for the small female and 6.2 kN for the all-female. These preliminary findings provide insights into injury tolerance of iliac bone for female occupant.

INTRODUCTION

The increasing integration of automated driving vehicles into the U.S. fleet and advancement in seat systems in recent passenger vehicles enables occupants to work, sleep, or socialize without the need to actively drive (Jorlöv et al. 2017). The National Highway Traffic Safety Administration (NHTSA) has recommended that manufacturers rigorously test emerging seating configurations in automated driving vehicles to ensure occupant safety (US-DOT, 2017). However, current restraint systems are verified exclusively based on conventional seating practices (NHTSA, 2012). The introduction of new seating arrangements may give rise to unforeseen issues, such as the interaction between the pelvis and the lap belt designed to prevent submarining. These changes could subject the pelvis to loading magnitudes not previously encountered in the existing vehicle fleet, potentially due to differences in interior design, such as the removal of the knee bolster.

Pelvic fractures have been documented in previous frontal sled tests conducted at a delta-V of 50 km/h using spring-controlled seat configurations, as reported in Uriot et al. (2015). In Richardson et al. (2021), two out of five tests with mid-size male subjects resulted in unilateral iliac wing fractures. Similarly, Uriot et al. (2015), reported that four out of eight specimens tested with front configuration seat stiffness sustained unilateral iliac bone fractures. Luet et al. (2012) observed pelvis fractures in five out of nine specimens, including four unilateral and one bilateral ilium fracture. In Trosseille et al. (2018), three out of nine test subjects sustained unilateral iliac bone fractures.

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MCW conducted a kinetic evaluation and injury assessment of 27 small female and obese postmortem human subjects (PMHS) in a frontal crash configuration. Initially, it was hypothesized that higher-velocity impacts, particularly in reclined seating configurations, would result in increased instances of lap belt submarining. However, these tests resulted in a significant number of PMHS sustaining pelvic bone fractures, especially in the ilium. These injuries were attributed to the direct loading of the lap belt against the bilateral ilium during the crash pulse. Additionally, an ongoing investigation of CIREN cases from 2018 to 2023, involving occupants with AIS2+ pelvis and abdomen injuries attributed to seatbelt use, identified at least six cases with fractures of the iliac wing. The most common fracture pattern involved outboard iliac bone fractures, affecting the anterior superior iliac spine (ASIS), as illustrated in Figure 1.

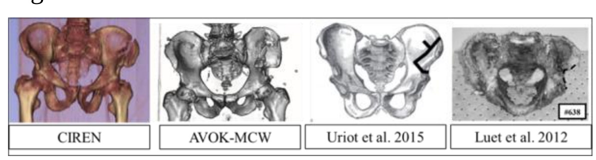

Figure 1. Illustrates notable iliac wing fractures (AIS2+) across CIREN case reviews, the MCW AVOK tests, and relevant literature.

The majority of the cited studies, along with CIREN cases and MCW tests, consistently report fractures occurring between the ASIS and the anterior inferior iliac spine (AIIS), with fracture lines extending into the iliac wing. Despite this, there is a paucity of studies dedicated to developing tolerance or injury risk functions for iliac bone injuries. This short communication aims to present a statistical analysis of the PMHS dataset, resulting in pelvis fracture risk curves specifically for female occupant groups.

METHODS

A total of 27 PMHS frontal sled tests were conducted using two groups of specimens representing (N=18) small female and (N=9) obese female. The detailed research workflow, experimental setup, and test configurations are comprehensively documented in our publications (Somasundaram et al. 2023) and also the data is available in the NHTSA biomechanics database. Briefly, all tests were performed using a semi-rigid, spring-controlled seat system, as referenced in the study by Uriot et al. [3].

The tests were categorized into baseline and countermeasure series based on seat stiffness and knee bolster configuration. Baseline tests were conducted using a stiffer seat, representative of the front seat in the Uriot et al. study. In contrast, the countermeasure series utilized either a softer spring seat, simulating the rear seat from the same study, or a knee bolster positioned approximately 100 mm from the occupant's knee. The baseline tests (12SF + 5ObeseF) were executed at two velocities—32 and 50 kph—and with two seatback recline angles—22° and 45°. All countermeasure series tests (2SF + 2ObeseF for each series) were conducted at a 50 kph delta V with a 45° reclined seatback configuration.

Fracture timing estimation

The timing of pelvis fractures was determined based on an abrupt change in strain and/or a peak in the strain rate as recorded by the strain gauge signals. Two strain gauges were strategically placed, one on each crest at the outer/lateral aspect of the iliac wing. In cases where multiple potential fracture timings were observed, the analysis prioritized times that aligned with significant changes in strain signal and strain rate, adjacent fracture occurrences to the iliac wing, and/or the window of change in the maximum belt loading.

Pelvis Injury Risk Curve (PV-IRC)

For the present analysis, we utilized a censored dataset comprising three types of cases: right-censored (no iliac bone fractures), uncensored (iliac fractures with known injury timing), and left-censored (iliac fractures but unknow injury timing). Given that the majority of iliac wing fractures occurred on the outboard or left pelvis, the lap belt load corresponding to the outboard pelvis was considered a potential metric for developing the PV-IRC. Next, using the Akaike Information Criterion (AIC), the Weibull distribution was identified as the best fit for the parametric survival function distribution for the current dataset. The IRC development methodology referenced from ISO standard TS18506 (Petitjean et al. 2011). The goodness of fit for the developed IRC was evaluated using the normalized confidence interval size (NCIS). NCIS values were categorized as follows: <0.5 (good), 0.5–1 (fair), >1–1.5 (marginal), and >1.5 (unacceptable) (Petitjean et al. 2011). The effects of covariates such as age and BMI were assessed using the Wald Chi-Square statistic, with a significance level set at $p < 0.05$.

RESULTS

For the present work, we developed two PV-IRCs based on the included surrogates: one for just small females (N=18) and another for all females (N=27), combining both obese females and small female cohorts. Table 1 presents the average age, BMI, pelvis injuries, and iliac bone fracture locations for each cohort.

Table 1. The sample size, demographics, and pelvis injury counts for each of the selected cohorts.

Occupants		Small female	All female
N		18	27
Age (yrs)		70 ± 15	67 ± 15
BMI (kg/m2)		18.5 ± 3.34	24.6 ± 9.44
Pelvis injury	Overall	10	13
	Iliac bone	7	9
Iliac bone fracture location	Outboard	4	5
	Inboard	1	1
	Bilateral	2	3

The developed PV-IRCs for the selected cohorts are shown in Figure 2. This plot illustrates the PV-IRC for predicting iliac bone fractures, using outboard lap belt force fitted to a Weibull distribution (solid line) with 95% confidence intervals (dashed lines). Table 2 presents selected results for injury risk levels of 10%, 25%, 50%, and 75% based on the outboard lap belt loads for each cohort.

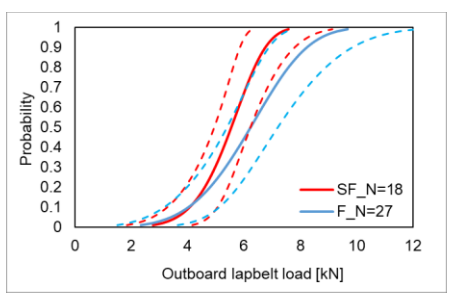

Figure 2. Shows the Pelvis Injury Risk Curves (PV-IRCs) for small female and all female cohorts.

Mean lap belt force corresponding to 50% injury probability level was 5.5 kN, for small female cohort, and 6.2 kN for all-female cohort, respectively. Age and BMI were not found to be significant variables ($p > 0.05$) for the PV-IRC in the small female cohort. However, the inclusion of obese individuals in the PV-IRC cohort shifted the risk curve to the right (Figure 3).

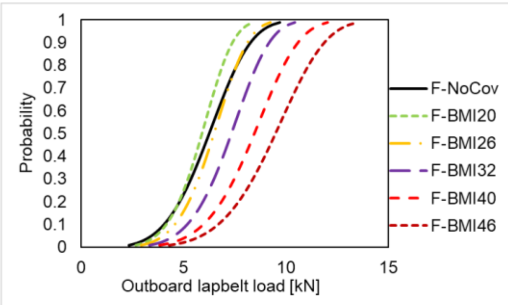

Figure 3. Depicts the PV-IRC for the all-female cohort (N=27) with varying BMI levels. Heavier BMI values shift the risk curve to the right.

DISCUSSION

A series of frontal sled tests were conducted with small and obese female specimens under varied boundary conditions. This study aimed to calculate the injury probability curve for iliac bone fractures caused by lap belt loading using data from these tests. None of the baseline tests conducted at 32 kph resulted in pelvis injuries. Out of 13 cases involving pelvis injuries, 9 tests included at least one iliac bone fracture, with the majority being unilateral and primarily in the outboard position. The potential reason would be attributed to non-symmetric belt engagement with the pelvis. On the inboard side, the lapbelt is connected to the buckle, while on the outboard side the lapbelt is directly fixed to the anchor, resulting in asymmetric loading of the pelvis. All the iliac wing fractures were reported only in the 50 kph baseline and soft spring test series.

Parametric survival analysis functions were used to develop IRCs for both the small female and all female cohorts. At a 50% probability level, the force values corresponding to the mean lap belt force were 5.5 kN for the small female cohort and 6.2 kN for the all-female cohort. These estimated tolerance values were higher than 4.9 kN lapbelt force derived from the isolated denuded iliac bones loaded under controlled lapbelt conditions (Moreau et al. 2023). When performing sled tests with PMHS, and especially with obese specimen, only part of the belt tension is due to the pelvic bone interaction. Part of it directly comes from the mass of soft tissues. Which is evident from Figure 3, the lapbelt load may increase due to obesity Therefore, the comparison of the force obtained with denuded iliac bone may be difficult.

Evaluation of the study reported IRC for matched-paired dummy test and human body simulation (unpublished) is future work .

CONCLUSION

In summary, two sets of PV-IRC for iliac bone fractures caused by lap belt loading were developed and presented in this study. The inclusion of individuals with higher BMI increased the fracture tolerance.

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