Effect of Dual Lap Belt Load-Limiters in Reclined Frontal Impact Sled Tests with PMHS of Varying Anthropometry and Sex

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ABSTRACT – Three frontal impact sled tests were conducted on postmortem human subjects of varying sex and anthropometry (mid-size female, mid-size male, and obese male) seated in a reclined posture. The subjects were restrained by a prototype seatbelt featuring dual lap belt load-limiters. Compared to previous studies, the mid-size female and male subjects, despite no submarining, experienced greater forward pelvis and lumbar spine excursions and differences in sagittal plane head trajectories but similar injuries. This work also provides novel kinetic, kinematic, and injury response data for an obese occupant subject to a reclined frontal impact sled test with dual lap belt load-limiters. Future work will provide expanded kinetic and kinematic response data obtained from these lap belt load-limited reclined sled tests.

INTRODUCTION

Advancements in autonomous vehicle technology have prompted research into the response and protection of occupants seated in alternative seating postures, including reclined postures. Recent studies have presented the response of postmortem human subjects (PMHS) seated in reclined postures and subjected to frontal impact sled tests ranging in impact severity, anthropometry, sex, and degree of recline (Baudrit et al., 2022, Richardson et al., 2020, Shin et al., 2023, Somasundaram et al., 2022, 2024). These studies have utilized common current restraint components such as pretensioners (PTs) and load-limiters (LLs), but LL use has primarily been limited to the shoulder belt. Further, pelvis iliac wing fractures caused by lap belt (LB) loading occurred tests at higher severities (Richardson et al., 2020, Shin et al., 2023). Östling et al. (2022) suggested utilizing a seatbelt system incorporating independent LLs in the shoulder belt and LB to mitigate iliac wing fractures. This study aimed to investigate the effect of dual LB LLs in a 3-point seatbelt on occupant kinetics, kinematics, and injuries in reclined frontal impacts for occupants of varying anthropometry and sex.

METHODS

Frontal impact sled tests were conducted on three adult PMHS of varying anthropometry (one mid-size female, one mid-size male, and one obese male) using a reverse acceleration sled system (1.4 MN ServoSled®, Seattle Safety, Auburn, WA, USA). PMHS testing procedures followed the ethical guidelines established by the National Highway Traffic Safety Administration and were reviewed and approved by the Biological Protocol Committee at the Center for Applied Biomechanics (CAB) as well as the University of Virginia Institutional Review Board – Human Surrogate Use Committee.

Methods established by Richardson et al. (2020) and Shin et al. (2023) were replicated for the current study (Figure 1). Each PMHS was subject to a 35 g, 50 km/h frontal impact sled pulse (Uriot et al., 2015) and restrained with a 3-point prototype seatbelt system including triple PT+LLs (shoulder belt and dual LB) and a dynamic crash-locking tongue. The dual LB LL consisted of a load-limited outboard retractor and a buckle sewn onto the webbing of a load-limited inboard retractor (Östling et al., 2022). Motion capture marker arrays were affixed to the head, T1, T8, T11, L1, L3, and the pelvis to track subject kinematics. Strain gauge rosettes were glued to the iliac wings to identify time of iliac wing fracture. Belt tension gauges were placed between the subject's right hip and the outboard retractor and between the subject's right shoulder and D-ring to measure lap and shoulder belt forces, respectively. The inboard retractor was mounted onto a 6-axis load cell to measure reaction forces and moments on the buckle side.

Positioning and orientation measures from Richardson et al. (2020) and Shin et al. (2023) were targeted for this test series. The primary positioning targets were torso angle, defined as the angle between the vertical and the line connecting the H-point to the acromion (mean ± SD: 46 ± 1°), and pelvis angle, defined as the angle between the horizontal and the line connecting

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the anterior superior iliac spine and the anterior inferior iliac spine (mean ± SD: 44 ± 2°).

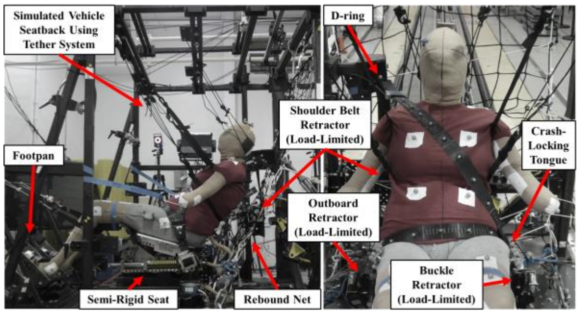

Figure 1. Test environment. Further details can be found in Richardson et al. (2020) and Shin et al. (2023).

RESULTS

Kinetic and Kinematic Response

The prototype seatbelt system effectively limited LB forces to 5 kN (Figure 2). Forward displacement of the pelvis was comparable between the female and male tests (221 mm vs. 231 mm), but much greater for the obese test (337 mm) partially due to the mechanical challenges faced during the test (see: Anti-Submarining Pan). Forward displacement of T11 was also comparable between the female and male tests (244 mm vs. 271 mm), but greater for the obese test (478 mm). Forward displacement of the head was again comparable between the two mid-size subjects (female: 547 mm; male: 572 mm), but greater for the obese subject (740 mm) (Figure 3).

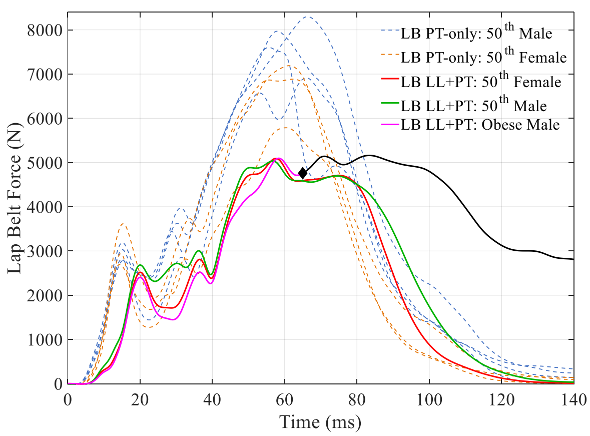

Figure 2. LB force time-history (CFC 60). LB PT only results for midsize male and female tests reproduced from Richardson et al. (2020) and Shin et al. (2023), respectively.

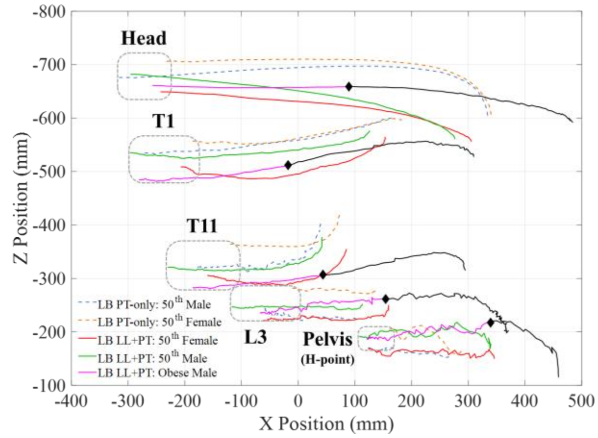

Figure 3. Sagittal plane trajectories of the head, T1, T11, L3, and pelvis (H-point). LB PT-only results averaged and reproduced from Richardson et al. (2020; male: n=4) and Shin et al. (2023; female: n=3).

Injury Response

All three PMHS sustained multiple injuries, but submarining was not observed in any test (Table 1). The lumbar fractures in the female and male tests were minimally displaced anterior compression fractures. The T12 fracture in the obese test was a two-column extension-type fracture most likely from rebound. All three sacrum fractures were minimally displaced transverse fractures. LB force at time of left iliac wing fracture for the male test was 4.7 kN, as determined from strain gauge signals.

Table 1. Test Matrix and Injury Summary.

Test	S0846	S0847	S0848
Subject	0982F	1044M	1089M
Mass (kg)	63	71	100
Stature (cm)	170	172	179
Submarining	—	—	—
Iliac Wing Fracture	—	✓ (Left)	—
Spine Fracture	✓ (L1)	✓ (L3+L5)	✓ (T12)
Sacrum Fracture	✓ (S4)	✓ (S4)	✓ (S3)
Sternum Fracture	✓	✓	✓
Rib Fracture (#)	11	5	3
Clavicle Fracture	—	—	—

Anti-Submarining Pan

During the obese male test, the welds holding the anti-submarining pan to the seat fixture failed (Figure 4). The data traces for the obese male are marked with a black diamond at the time of weld failure (65 ms) and switch from magenta to black at this time (Figure 2; Figure 3). Despite this mechanical limitation, the LB did not visibly slip above the pelvis, and the LB force did not decrease until after rebound (100 ms).

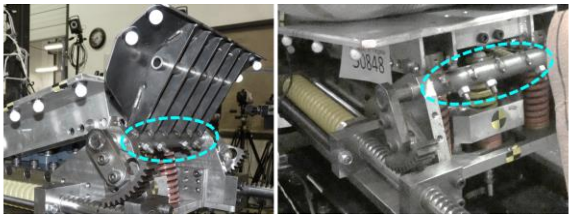

Figure 4. Anti-submarining pan weld failure.

DISCUSSION

Kinematic Response Comparison

The payout from the inboard and outboard LB retractors limited LB force and allowed for greater forward pelvis (approximately 50% increase) and lumbar spine excursion in the LB LL+PT tests (Figure 2; Figure 3). Sagittal plane kinematics of the thoracic spine remained comparable between the LB PT-only and LB LL+PT tests despite some differences in initial position (Figure 3). The LB PT-only tests resulted in a constant vertical head position and downward motion just before rebound, whereas in the LB LL+PT tests, the head moves downward from the onset of the pulse (Figure 5).

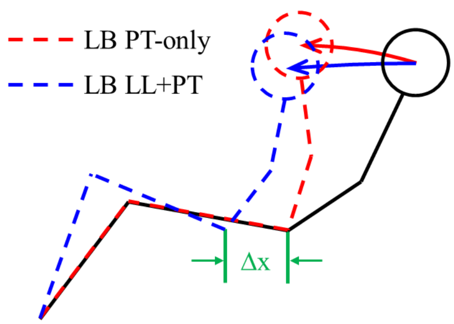

Figure 5. Whole-body motion difference between LB PT-only and LB LL+PT tests.

Injury Response Comparison

The LB remained well engaged with the anterior pelvis (i.e., no submarining) even with dual LB LLs and the resulting increased forward pelvis excursion. However, the LB LL did not fully prevent pelvis fracture. The location and pattern of the iliac wing fracture in the female test was similar to those observed by Richardson et al. (2020) and Shin et al. (2023). Moreau et al. (2023) found that iliac wing fracture tolerance varies widely, ranging from 1.5 to 10+ kN, so the presence of an iliac wing fracture is plausible despite the load-limiting of the lap belt. Sacrum fractures were evident in all tests from the current study, which is consistent with the findings presented in Richardson et al. (2020) and Shin et al. (2023). Overall, injury patterns were consistent between the LB PT-only tests and LB LL+PT tests, with occurrences of lumbar spine, sternum, and rib fractures across anthropometry and sex (Richardson et al., 2020; Shin et al., 2023). However, no clavicle fractures occurred in the current study. Clavicle fractures have been theorized to alleviate lumbar spine fractures (Shin et al., 2023). Baudrit et al. (2022) conducted reclined PMHS sled tests with shared boundary conditions (e.g., sled pulse, semi-rigid seat) and LB LLs. These tests resulted in no submarining and lumbar spine fractures, akin to the results of the current study, yet no anterior iliac wing fractures were observed, which may be due to the lower force limit (3.5 kN compared to 5 kN of the current study).

Future Work

The lack of a seat cushion in the seat limits the results of the current study from being applied directly to reclined occupant protection in real vehicle seats. Other countermeasures, such as a seat track load-limiter (Östling et al., 2021), may be considered to mitigate injury to reclined occupants.

CONCLUSION

Three frontal impact sled tests were conducted on PMHS of varying anthropometry and sex seated in a reclined posture and restrained with dual LB LLs. The LB LL+PT system permitted greater forward pelvis displacement than past LB PT-only systems but still successfully prevented submarining. The tests conducted provide reference PMHS response data for use in biofidelity evaluations of physical and virtual human body models and an expanded kinetic and kinematic analysis will be provided in a future publication.

ACKNOWLEDGMENTS

The authors would like to acknowledge Autoliv for providing financial and technical support for this study. The authors would also like to thank everyone at the UVA CAB who assisted with this project.

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