SHORT COMMUNICATION: STAPP CAR CRASH CONFERENCE

Sex Specific ATD Assessments for Lower Extremity Injuries

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ABSTRACT – Increased risk of lower extremity injuries for shorter stature drivers and women continues to be of concern. Nine sled tests were conducted to evaluate the effect of the heel-to-floor gap, six with the HIII 5th Female ATD and three with the 50th Male. Feet were positioned with and without a gap to the floor, with consistent flexion angles. Regardless of foot position relative to the floor, injury metrics were found to be systematically higher for the 5th Female ATD, 68% higher for the right foot on pedal position than for the 50th Male ATD. Additional study combining more factors affecting shorter stature drivers and women is warranted.

INTRODUCTION

Morbidity from lower extremity injuries continues to be of concern in frontal crashes (Craig et al. 2024). Injury can still occur with minimal to no intrusion into the footwell with drivers being the likeliest injured, suggesting pedal interaction as a key mechanism (Crandall et al. 1998). Of the driver occupants, those of shorter stature and women have increased risk of lower extremity injuries in frontal crashes (cf. Rudd 2009).

Positioning during emergency braking trends towards plantarflexion accompanied by a heel-to-floor gap for women (Palmertz et al. 1998). Prior impactor tests have established that increased pedal interaction elevates lower extremity injury risk (Funk et al. 2012; Rudd et al. 2004). Additionally, cadaver studies demonstrate that an initial plantarflexion condition exacerbates tibial loading and permits greater dorsiflexion excursion, indicating both foot posture and pedal engagement can compound injury risk (Rudd et al. 2004; Smith et al. 2005). While prior work has examined plantarflexion and pedal interaction, the specific contribution of heel-to-floor gap has received less direct investigation (Crandall et al. 1996; Rudd 2009).

METHODS

A representative driver compartment of a mid-size sedan was constructed, consisting of a driver-side toepan, knee-bolster assembly, electronically adjustable seat, and outboard pretensioner equipped lap-shoulder belt. Rigid polyurethane foam was used as a surrogate for the knee bolster, consistent with prior validation work (Albert et al. 2016). The accelerator pedal was replaced with a right-side rigid brake pedal in a depressed condition to assess right/left differences. The steering wheel column and airbags were not simulated due to their limited influence on lower extremity injuries (Rudd et al. 1998).

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To assess the influence of foot placement, nine sled tests were conducted using the Wayne State University HyGE sled. The first six tests used the 5th Female ATD (HIII 5th) with shoes (FIGURE 1). The setup provided a raised foot and a lowered foot condition that could be tested simultaneously. This setup was also used to assess feasibility of future whole body cadaveric testing using both legs. Three HIII 5th tests were conducted with the right foot raised and left foot contacting the floor, then foot positions were swapped for the next three tests. For the raised condition, the foot was positioned on the brake pedal, with the heel 31.75 mm (1.25 inches) above the floor to simulate behavior of occupants with shorter foot size in braking. This position aligned well with measurements from a surrogate sedan and predictive posture differences for a 5th Female, such as the steeper tibia angle (Reed et al. 2000). The floor height was varied to create the raised versus lowered conditions, keeping the ATD/brake pedal positioning consistent. Three additional tests were conducted using the 50th Male ATD (HIII 50th) with shoes. Both feet were positioned in contact with the floor and brake pedals.

Figure 1: HIII 5th Female test configuration

Equipment

High-speed video cameras (nac Image Technology, Inc. Tokyo, Japan) mounted overhead and on both sides of the lower extremities captured kinematic movement, supplemented by 3-D kinematic tracking using a high-speed motion capture system (Vicon Motion Systems, Yarnton, Oxfordshire). Each brake pedal was equipped with a load cell (LWPF1, Interface, Inc., Scottsdale, AZ) and accelerometer (7264D, Endevco, Halifax, NC) for inertial compensation. Similarly, the vehicle floor consisted of an identical load cell for each foot, lined with automotive carpet, and identical accelerometers. Sled acceleration was measured using two additional Endevco 7264D accelerometers. A HyGE pin with an acceleration profile similar to US NCAP 35 mph barrier tests was used.

Precise and repeatable positioning was achieved with a 6-axis coordinate measurement machine (Hexagon Metrology, North Kingstown, RI). Positional variance averaged 10.0 ± 3.1 mm across all tests.

Signals were filtered according to SAE J211 specifications with a normalized injury metric, the Tibia Index (TI), calculated in accordance with SAE J1727. The critical force and moment values were 22.9/35.9 kN and 115/225 Nm for the 5th Female and 50th Male, respectively. Comparisons were evaluated for statistical significance using MATLAB's two-sample t-test with significance defined as $p < 0.05$.

RESULTS

The sled produced consistent pulses with an average duration 126.6 ± 0.5 ms, mean peak acceleration of 23.5 ± 0.2 g, and mean ΔV of 52.8 ± 0.4 km/h. Characteristic averages of the right brake pedal load-cell show the 5th Female sustained higher forces than the 50th Male (Figure 2). The gap did not affect the 5th Female's right brake pedal forces outside a ±1 standard deviation.

5th Female Hybrid III ATD

In the raised condition, neither foot interacted with the floor until after maximum engagement with the brake pedal. The average left TI in the raised condition was 0.91 ± 0.15 and 0.83 ± 0.10 for the floor contact condition. Conversely, the right lower extremity average TI was higher in the floor contact condition at 0.62 ± 0.10 than the raised condition at 0.55 ± 0.07.

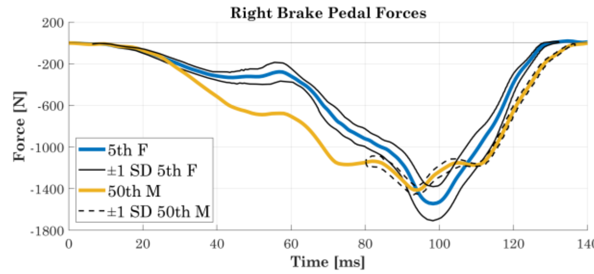

Figure 2: Right brake pedal forces from both ATDs. Mean values and ±1 SD corridors.

50th Male Hybrid III ATD

The right TI averaged 0.37 ± 0.01 and the left 0.36 ± 0.20. Larger variance was observed for the left TI as the heel detached carpet on the floor load cell in two tests. In the test without separation, the heel remained in contact with the floor load cell with a TI of 0.64.

For these crash profiles, all tests fell below a TI of 1.0 with the exception of the left lower extremity in one HIII 5th test (FIGURE 3).

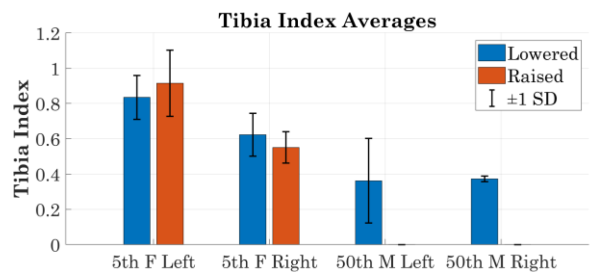

Figure 3: TI averages for lowered floor contact and raised conditions

Two sample t-tests were performed to determine significance of differences between the tested ATDs and foot positions. Relative to the two ATDs, the TI was higher for the HIII 5th (p=0.001). Raised or lowered conditions showed no statistical significance for the HIII 5th.

DISCUSSION

There were systematic differences between the HIII 5th and 50th in all conditions tested. Based on the underlying biomechanical differences between the HIII 5th and 50th illustrated by the TI differences in critical values, the higher TI for the HIII 5th suggests anthropometry may be the primary contributor to the persisting lower extremity injury increase in women over men.

Feet rotated about the pedal with upward movement, then downward movement occurred later as the feet unloaded from the pedals for the HIII 5th. Therefore, the actual height of the gap appeared to have no kinematic effect before maximum pedal engagement if the feet were not already in contact with the floor, with positioning otherwise equal. The shallower tibia angles and larger feet of the HIII 50th afforded it the opportunity to contact the floor throughout the crash pulse. Consequently, lower peak brake pedal forces for the HIII 50th were attributed to greater partitioning of forces between the brake pedals and floor, given both feet were touching.

There were systematic differences between the HIII 5th and the HIII 50th regardless of foot position with respect to the floor. Worst-case pinning of the HIII 50th's left foot to the floor, observed in Test 9, still showed lower TI than for the HIII 5th.

Asymmetrical loading resulted in higher TI values in the raised condition for the left leg, and the opposite for the right leg for the HIII 5th. Given the outboard position of the pretensioner, this result suggests that bilateral pretensioners may be valuable for reducing right lower extremity injuries in 5th females, although the presence of bilateral pretensioners have not yet been investigated on certain vulnerable populations. Further investigation into the role of pretensioners and asymmetrical lower extremity loading may be warranted.

Limitations

The surrogate vehicle environment lacked frontal airbags owing to limited influence on lower extremity injuries. Knee bolster airbags were also not used, though protective effects from increasingly common knee bolster airbags may offer future injury reduction. This study did not assess different floor gaps and flexion angles. Such study may contribute valuable understanding of detailed differences in injury response between men and women in car crashes. Further, rigidly mounted non-deformable pedals likely overestimate foot-pedal loads compared to deformable systems.

CONCLUSION

We found the presence of the investigated gap did not eliminate the TI injury disparity for the right foot of the HIII 5th relative to the HIII 50th. Risk of lower extremity injuries assessed using Tibia Index was systematically larger for the HIII 5th than the HIII 50th in similar conditions. Future work should integrate cadaveric testing, knee bolster airbags, deformable pedals, and combined effects of plantarflexion angles with floor gaps.

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