Small Female Acceleration Response Corridors and Updated THOR-05F Biofidelity Ranking: Preliminary Results from Nearside Frontal Oblique Impact Tests

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ABSTRACT – The objective of the study was to develop response corridors of small female post-mortem human subjects (PMHS) and evaluate the biofidelity of the THOR-05F in nearside oblique frontal impacts using the Biofidelity Ranking System (BRS). Matched pair tests were conducted with five restrained PMHS at 8.4 m/s and three repeat tests with the THOR-05F under similar conditions. Accelerations of the upper and lower thoracic spine, lumbar spine, and pelvis were used to develop corridors using the traditional mean ± 1 standard deviation (SD) method. They were used to evaluate the biofidelity of the THOR-05F. The mean ± 1SD BRS scores ranged from 0.59 ± 0.01 to 1.09 ± 0.02 for different regions of the spine and pelvis, indicating excellent biofidelity. Additional analyses using BRS for different signals and obliquities are needed to further evaluate the biofidelity of the THOR-05F.

INTRODUCTION

Crashworthiness assessments are conducted in the automotive field using anthropomorphic test devices (ATDs) that have proven biofidelity and ATD injury criteria. ATDs are often based on size. Small female, mid-size male, and large-size male ATDs are the most common with approximate weights of 50 kg, 75 kg, and 104 kg, respectively. Hybrid III ATDs are used for frontal impacts, and EuroSID-II (ESII-re) are used for side impacts in the U.S. Federal Motor Vehicle Safety Standards (FMVSS) 208 and 214. The Test Device for Human Occupant Restraint (THOR) is an advanced ATD that is developed for frontal impacts, and it has small female and mid-size male versions (termed as THOR-05F and THOR-50M).

The biofidelity of any ATD is assessed using responses developed from post-mortem human subject /surrogate (PMHS) tests. Tests using male-only and female-only PMHS are most appropriate to assess the biofidelity of male and female ATDs, respectively. For ATDs designed with an intent for use in frontal impacts, exposures may include both pure frontal and oblique orientations, requiring biofidelity to be assessed for both. While pure frontal impact responses of male and female PMHS are reported in published studies (e.g., Cavanaugh and Yoganandan, 2015), similar studies are lacking for small females in frontal oblique impacts. One study reported the kinematic corridors of the head, spine, and pelvis using motion capture tracking but did not explore sensor data that would be comparable to data collected using the THOR ATD (Humm et al., 2018). The objective of the study was to develop response corridors of small female post-mortem human subjects (PMHS) and evaluate the biofidelity of the updated THOR-05F in nearside oblique frontal impacts using the Biofidelity Ranking System (BRS). Updates since the original, 2018-edition of the THOR-05F include rib material and geometry changes, improved lower IR-TRACC brackets and relocation of lower IR-TRACC mounts, and an updated ankle design (Hutter, 2024).

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METHODS

Specimen positioning and instrumentation

Unembalmed female PMHS were pre-screened for bloodborne pathogens. Radiographs, and computed tomography images, were obtained. Lumbar spine bone mineral density was calculated. The specimens were clothed in a leotard, and a mask was used to cover the head and facial structures. They were positioned on the platform of a rigid seat on a sled and restrained with a three-point belt. The head was aligned with respect to the Frankfurt plane. Triaxial accelerometers (6DX Pro, Seal Beach, CA) were attached to the upper and lower thoracic spines (T1 and T8), lumbar spine (L2), and pelvis/sacrum. The nearside oblique frontal impact was oriented at thirty degrees (11 o'clock).

Impact Loading and Biomechanical Data

Oblique frontal impact sled tests were conducted at 8.4 m/s. Biomechanical data were gathered and processed according to the Society of Automotive Engineers specifications (SAE 2022). Acceleration signals were normalized to the small female weight of 50 kg using the equal-stress equal-velocity method and appropriate scale factors for each specimen were used (Yoganandan et al. 2014). Normalizing factors ranged from 0.80 – 1.39 across all specimens. Response corridors were developed from the filtered acceleration-time signals using the traditional, mean ± 1 standard deviation (SD) approach, calculated by averaging the ordinate at each time point and expressed as the time varying mean ± 1SD curves. Corridors were developed for the anteroposterior and vertical acceleration responses. They were developed for the upper and lower thoracic spine, lumbar spine, and pelvis.

Matched-Pair Tests with THOR-05F

Matched-pair tests were conducted using the updated THOR-05F. Three repeat tests were conducted. The response corridors were used to evaluate the biofidelity of the ATD. The Biofidelity Ranking System (BRS, also termed BioRank), was used according to methods published elsewhere (Hagedorn et al., 2022). Briefly, BRS optimized the alignment of signals from the ATD to the mean PMHS responses. BRS score only accounted for the shape and magnitude of the signals. During the BRS score calculation process, phase shift was checked and found to be reasonable. The phase shifts are not reported in this short communication. PMHS data were not shifted. Loading and unloading regions of the signals were included in the BRS analysis. BRS scores equal to or less than 1 were classified as "Excellent"; greater than 1 but equal to or less than 2 were termed "Good"; and greater than 2 were considered "Poor" (Hagedorn et al. 2022).

RESULTS

PMHS Response Corridor Results

The mean age, stature, weight, sitting height, body mass index, and bone density of five specimens were 70 years, 1.63 m, 46.3 kg, 0.89 m, 17.5 kg/m^2, and 105 mg/cc, respectively. The mean peak values of the resultant accelerations of the sacrum, lumbar spine, and lower and upper thoracic spines were 11.5, 10.6, 12.5 and 14.3 g, and their time of occurrences were 39.6, 83.2, 81.9 and 75.4 ms, respectively. The mean ± 1SD method produced typical acceleration response corridors shown in Figure 1.

THOR-05F Biofidelity Ranking System Results

For each region, BRS score was determined for each test. The minimum DCAD method between 0-300 ms was used for alignment; BRS score was calculated over the same duration. The mean from all tests was then taken as the final value for a given region. The BRS score for the upper thoracic spine was 0.71 ± 0.03 (X) and 1.09 ± 0.02 (Z), lower thoracic spine was 0.82 ± 0.04 (X) and 0.83 ± 0.01 (Z), lumbar spine was 0.97 ± 0.03 (X) and 0.59 ± 0.01 (Z), and pelvis was 0.69 ± 0.00 (X) and 0.62 ± 0.02 (Z). Figure 2 shows a typical acceleration response corridor overlaid with the ATD responses and the BRS score.

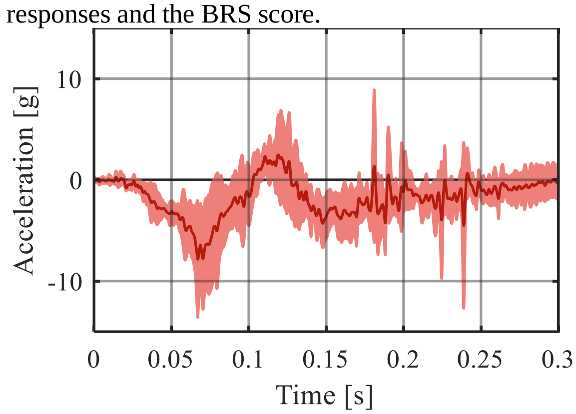

Figure 1: Sample upper thoracic anteroposterior acceleration response corridor using the standard method of mean ± 1SD. Solid curve corresponds to the mean, and shaded area represents the one standard deviation zones around the mean response.

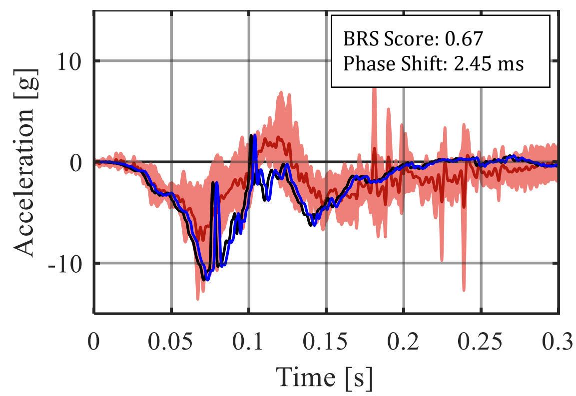

Figure 2: Sample BRS output for the upper thoracic spine anteroposterior acceleration. Solid red curve corresponds to the mean, and shaded area represent the one standard deviation zones around the mean response from the PMHS data. Black and blue curves correspond to the raw and phase-shifted THOR-05F data. The left and right edges of figure boundaries represent the window over which alignment and BRS score were determined. Numerical data are shown in the legend.

DISCUSSION

This is the first study to develop response corridors from using small female specimens tested under frontal oblique impacts in the nearside condition. The traditional mean ± 1SD method has been used to develop response corridors from sled tests for male-only, and male and female PMHS under pure frontal and pure lateral, and side oblique impacts (Maltese et al., 2002, Cavanaugh and Yoganandan, 2015, cited list is not inclusive).

The BRS scores of the THOR-05F for different body regions as measured by the acceleration responses were found to be excellent in each region and for each direction (except upper thoracic vertical direction, which was in the good category) The aggregate rating was also deemed as excellent. It is important to determine the BRS score of the thorax based on deflection metrics (IR-TRACC sensors are available in the ATD) and other body regions, such as the head, to reinforce the present findings. Furthermore, because the THOR-05F is also used under far-side conditions, it is important to follow the methods described in the present study to more comprehensively determine the biofidelity of the ATD.

While the study used only female PMHS tests to develop corridors, the limitations of the study include sample size issues, one velocity, and use of sensor measured acceleration histories. While the study used the traditional mean and 1 SD method for corridor development, it may be appropriate to examine the efficacy of other methods for corridor development. Additional studies are also needed to develop corridors using other biomechanical data such as chest deflections. These are future study topics.

CONCLUSION

The traditional method of developing human response corridors were found to be satisfactory for the present dataset. The BRS scores were in the excellent category for the upper and lower thoracic spines, lumbar spine, and pelvis. Additional tests and analysis covering other biomechanical variables, and far-side oblique conditions, are needed to more comprehensively determine the biofidelity of the THOR-05F ATD.

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DISCLAIMER

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