Comparison of the THOR-AV-5F ATD and 5th Percentile Female Volunteer Responses during Low-Speed Frontal and Frontal-Oblique Sled Tests

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ABSTRACT

As crash avoidance technologies like autonomous emergency braking (AEB) become more prevalent, it is increasingly necessary to study occupant responses during these scenarios to understand their implications on occupant safety. The low speed and long duration of pre-crash braking and low severity crash events provide sufficient time for muscle activation to affect occupant response. Unfortunately, this effect is not accurately captured in post mortem human subject response data from high severity tests that are typically used to validate anthropomorphic test devices (ATDs). Performing matched low-speed volunteer and ATD tests can provide insight into the validity of using ATDs to assess occupant safety during low severity events. The THOR-AV-5F ATD was developed recently and was designed to represent 5th percentile females in autonomous vehicles. Its biofidelity has not yet been assessed in low severity tests. The objective of this study was to quantify the occupant response of the THOR-AV-5F during low-speed frontal and frontal-oblique sled tests, and compare the ATD response to relaxed and braced 5th percentile female volunteer responses during matched tests. Six 5th percentile female volunteers experienced low-speed sled tests in two test orientations (frontal and frontal-oblique) and at two pulse severities (1 g and 2.5 g), with two muscle conditions (relaxed and braced) per pulse severity. Matched THOR-AV-5F sled tests were performed for each test condition. Reaction forces at each test buck interface and head, neck, and sternum accelerations were measured for the volunteers and ATD during each sled test. Overall, the THOR-AV-5F reaction forces and accelerations exhibited some differences compared to the volunteers, but were generally more similar to the relaxed volunteers than to the braced volunteers across all test conditions.

INTRODUCTION

Crash avoidance technologies like autonomous emergency braking (AEB) are becoming more prevalent and standard in new vehicles, particularly in autonomous vehicles (AVs) (Cicchino, 2017), (NHTSA, 2020). As such, it is increasingly necessary to study occupant responses during these scenarios to understand their implications on occupant safety. Anthropomorphic test devices (ATDs) are commonly used to evaluate occupant safety during vehicle crashes, but are primarily validated based on the response of post-mortem human subjects (PHMS) during high-severity tests (Albert et al., 2018a, 2018b), (Parent et al., 2017), (Wang et al., 2021). PMHS inherently lack muscle activity and may not be able to capture the nuances of live human response, especially during low-severity events (Beeman et al., 2012). Pre-crash braking associated with AEB and low-severity crash events occur at low speeds and over long durations, providing sufficient time for muscle activation to affect occupant response (Ejima et al., 2007, 2008, 2009), (Graci et al., 2021), (Ólafsdóttir et al., 2013), (Östh et al., 2013). Consequently, volunteer testing provides valuable data that human surrogates are not capable of capturing accurately.

Performing matched low-speed volunteer and ATD tests can provide insight into the validity of using ATDs to assess occupant safety during low-severity events (Beeman et al., 2012), (Parenteau et al., 2022), (Yaguchi et al., 2006), (Yamazaki et al., 2008). Understanding how current ATDs respond during low-severity events and comparing to relevant volunteer responses could also potentially help develop and improve future ATDs for use as tools in assessing occupant safety during these events. The THOR-AV-5F ATD was developed recently and was designed to represent 5th percentile females in AVs (Kinsky & Kleeßen, 2022). Changes from the previous THOR-5F iteration include new neck, abdomen, lumbar spine, and pelvis designs (Wang, 2022). The THOR-AV-5F is still being validated and its biofidelity has not yet been assessed in low-severity tests. Therefore, the objective of this study was to quantify the occupant response of the THOR-AV-5F during low-speed frontal and frontal-oblique sled tests, and compare the ATD response to relaxed and braced 5th percentile female volunteer responses during matched tests.

METHODS

Six female volunteers (24.0 ± 2.8 years old), approximately 5th percentile in height (156.7 ± 6.1 cm) and weight (50.0 ± 2.4 kg), participated in this study (Table 1). Volunteer testing was approved by the Virginia Tech Institutional Review Board (IRB #17-1008) and each volunteer signed an informed consent form at the start of each visit.

Table 1: Volunteer demographic, anthropometric, and test day orientation information.

Age (years)	Height (cm)	Weight (kg)	1st Test Day Orientation	2nd Test Day Orientation
26	159.7	50.6	0°	330°
27	164.6	52.2		
25	154.8	50.9		
19	158.7	51.8	330°	0°
24	155.9	48.4		
23	146.5	46.0		

Test Conditions

Each volunteer experienced multiple low-speed sled tests on two separate test days (7-10 days apart). On a given test day, the volunteers experienced either pure frontal sled tests, where the principal direction of force (PDOF) was 0°, or frontal-oblique sled tests, where the test buck was rotated clockwise 30° to obtain a PDOF of 330° (Figure 1). Half the volunteers (3 females) experienced frontal tests on their first test day, and half the volunteers experienced frontal-oblique tests on their first test day (Table 1). All volunteers experienced both test orientations between their two test days.

On each test day, the volunteers experienced four sled tests at two pulse severities (1 g and 2.5 g), with two muscle conditions (relaxed and braced) per pulse severity (Figure 2-Figure 3). The 1 g pulse was designed to simulate an autonomous braking event and the 2.5 g pulse was designed to simulate a low-severity crash (Figure 2) (Graci et al., 2021), (Hulshof et al., 2013), (Linder et al., 2001). The sled tests were conducted in the same order on each test day: 1 g relaxed (Δv = 9.47 kph), 1 g braced (Δv = 9.39 kph), 2.5 g relaxed (Δv = 5.33 kph), and 2.5 g braced (Δv = 5.09 kph).

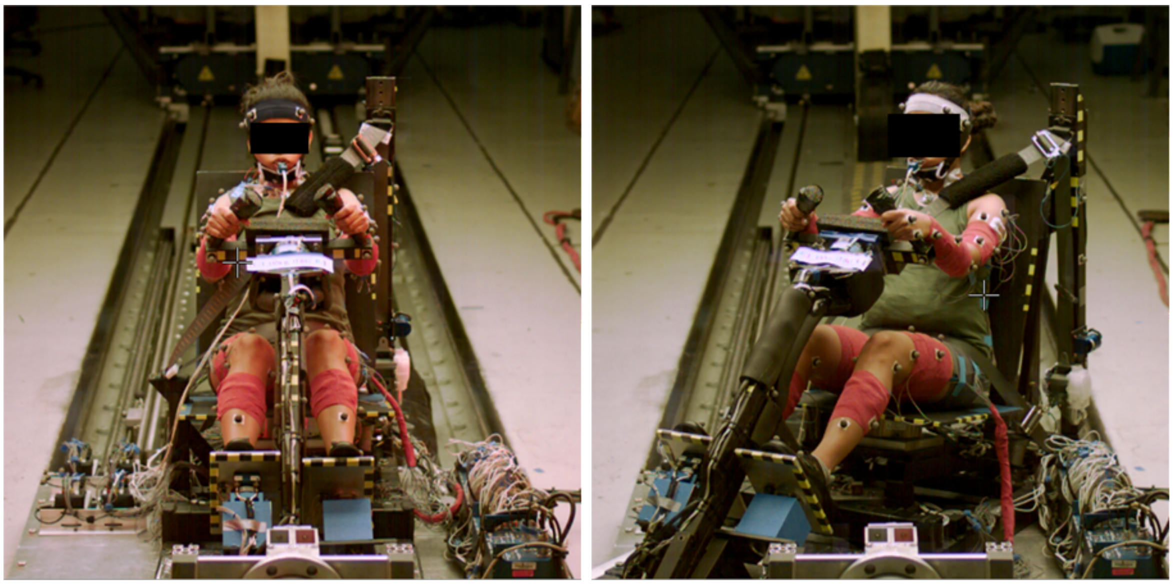
Figure 1: A female volunteer in the frontal (left) and frontal-oblique (right) test orientations.

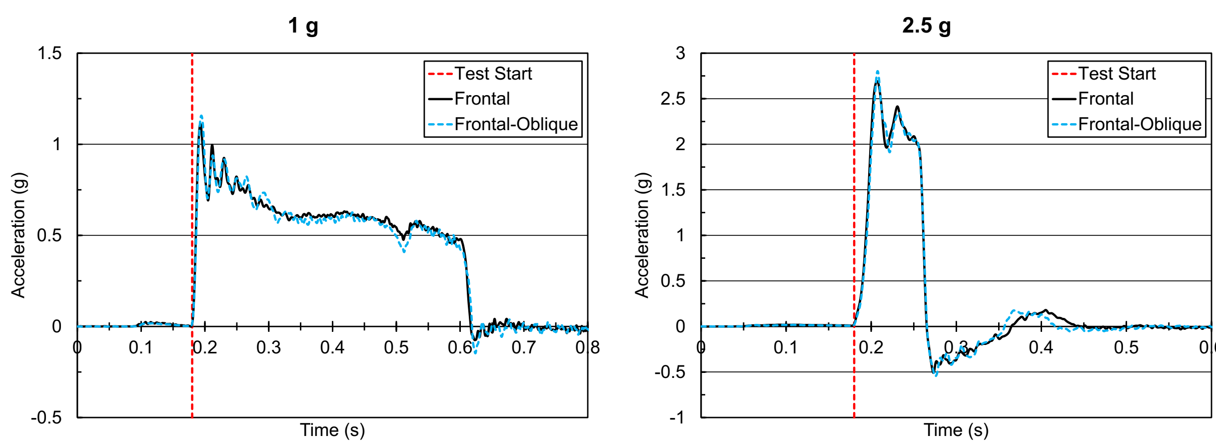

Figure 2: Average time histories of the sled pulse accelerations, aligned with the principal direction of force (PDOF), for the 1 g (left) and 2.5 g (right) pulse severities.

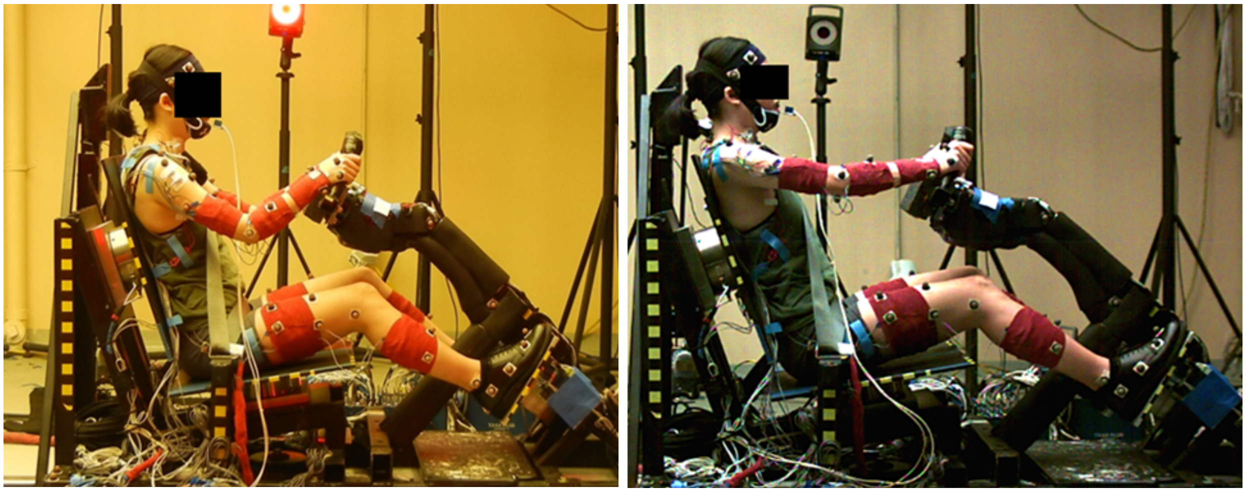

Figure 3: A female volunteer at the test start of a relaxed (left) and braced (right) frontal test.

For the relaxed tests, the volunteers were unaware of the test start but were told that the pulse would be triggered within the next few minutes. They were instructed to sit in a relaxed manner, face forward, and focus on a monitor playing a television show or movie (Figure 3). When the volunteers appeared relaxed, relatively still, and focused on the monitor, the pulse was triggered out of sight. For the braced tests, the volunteers were aware of the test start and were given a countdown before each test ("3...2...1...Go"). They were instructed to sit in a manner similar to the relaxed tests at first and to begin bracing two seconds prior to the test start by pushing with maximum effort onto the test buck using their arms, legs, and torso (Figure 3).

Experimental Set Up

The sled tests were performed using a custom rigid test buck and mini-sled accelerated by a pneumatic piston. The test buck, originally designed for 50^{th} percentile males, was modified for 5^{th} percentile females by installing rigid aluminum spacers at each volunteer-test buck interface including the left and right foot pedals, steering column, seat pan, and seat back (Figure 4). These modifications positioned the reaction surfaces to accommodate the anthropometry of 5^{th} percentile females. A standard, 3 kN load-limiting, United States driver-side, three-point seatbelt was used for all sled tests (Figure 1). The slack in the seatbelt was manually removed prior to each test start.

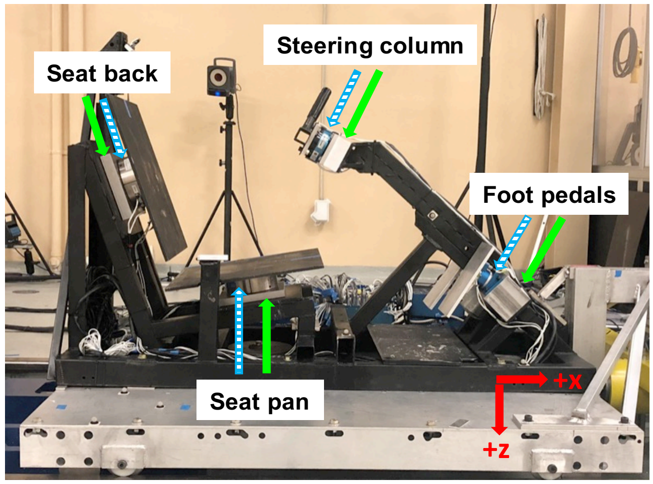

Figure 4: Custom rigid test buck and mini-sled instrumented with reaction load cells (striped blue arrows) and modified for 5th percentile female volunteers with rigid aluminum spacers (green arrows) at each volunteer-test buck interface.

Instrumentation

Reaction Forces: The test buck was instrumented with multi-axis load cells at each volunteer-test buck interface to quantify the reaction forces of the volunteers during each sled test (Figure 4). Six-axis load cells were installed at the left foot pedal (Denton-1716A, Rochester Hills, Michigan, United States), right foot pedal (Denton-1794A), seat pan (Denton-2513) and seat back (Denton-2513). A five-axis load cell was installed at the steering column (Denton-1968). Custom rigid motion blocks with three uniaxial accelerometers (7264C-2000, Endevco, San Juan Capistrano, California, United States) were rigidly mounted to each volunteer-test buck reaction surface to quantify the accelerations during each sled test. These accelerations were recorded in order to inertially compensate the reaction forces.

Volunteer Accelerations: Volunteer head linear accelerations and angular velocities were measured during each sled test using a motion block with three uniaxial accelerometers and three angular rate sensors (6DX-Pro, DTS, Seal Beach, California, United States) rigidly mounted to a metal dental tray (Figure 5). A thermoplastic mouth guard was molded for each volunteer to bite on and ensure a safe and tight junction with the dental tray. The dental tray was positioned in the center of the volunteers' jaws (mediolaterally) and lateral view pictures were taken before each sled test to record the positioning relative to the approximate head center of gravity (CG) (Figure 5). The volunteers also wore a custom chinstrap to help ensure that their jaws remained closed during the entirety of each sled test. Volunteer neck and sternum linear accelerations were also measured using motion blocks with three uniaxial accelerometers (7264C-2000, Endevco) attached at the seventh cervical vertebra (C7) and suprasternal notch, respectively, with adhesive patches (Figure 5).

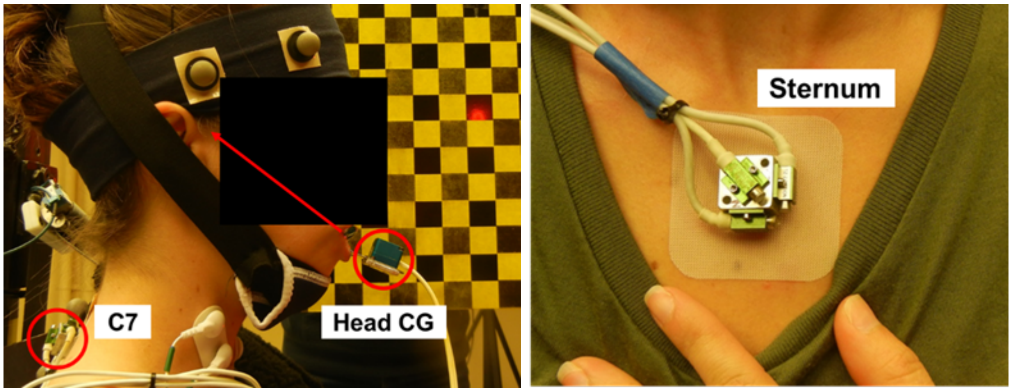

Figure 5: Locations of the motion blocks used to measure volunteer head, neck, and sternum accelerations.

Matched ATD Sled Tests

Matched sled tests were performed using the THOR-AV-5F ATD (Figure 6). Three tests were performed for each test condition (frontal 1 g, frontal 2.5 g, frontal-oblique 1 g, and frontal-oblique 2.5 g). The same experimental set up was used to conduct the matched ATD sled tests including the test buck and sled, seatbelt, and instrumentation to measure test buck reaction forces and accelerations. THOR-AV-5F head, neck, and sternum accelerations (analogous to the volunteers) were measured during each sled test using three uniaxial accelerometers (7264C-2000, Endevco) at the head CG and first thoracic vertebra (T1), and one uniaxial accelerometer (7264C-2000, Endevco) at the mid-sternum (x-direction only).

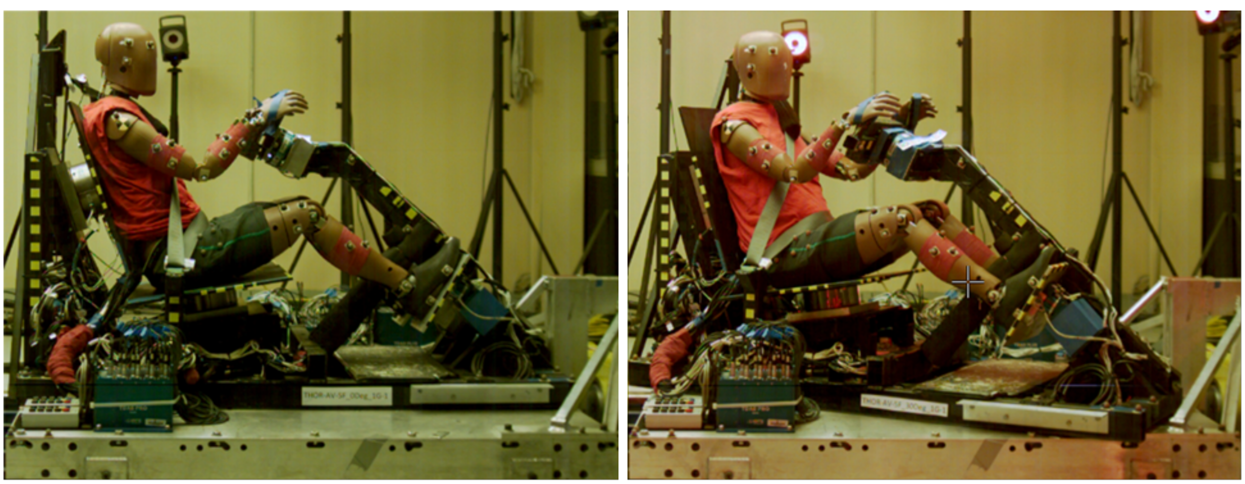

Figure 6: The THOR-AV-5F in position at the test start of a frontal (left) and frontal-oblique (right) test.

ATD Positioning: Before each sled test, the THOR-AV-5F was positioned on the seat back, seat pan, and foot pedals mediolaterally by lining up the torso, pelvis, and feet, respectively, with centerline markings on each ATD-test buck interface. The ATD was then positioned on the test buck to match the average female volunteer initial joint angles from the relaxed tests as closely as possible. Initial ATD joint angles were confirmed visually using a goniometer. The ATD's hands were secured to the steering wheel with masking tape. Consistent ATD positioning was confirmed by checking the head angle, shoulder belt angle, shoulder belt location, and knee-to-knee distance using a ruler and goniometer. Consistent ATD positioning was also confirmed by monitoring the angles output by tilt sensors located at the head, middle thorax, lower thorax, and pelvis/lumbar areas. Similar to the volunteer sled tests, the slack in the seatbelt was manually removed prior to each test start.

An onboard data acquisition system (TDAS Pro, DTS) was used to record all forces and accelerations during each volunteer and ATD sled test (20,000 Hz sampling rate). Data were recorded for three seconds pre-trigger and three seconds post-trigger for each sled test. Data from each sled test were time-shifted so that the initiation of the sled pulse occurred at 180 ms (test start) for each test. The time histories presented in the following sections were limited to data from 100 to 900 ms.

Data Processing and Analyses

Reaction Forces: Reaction forces were first filtered at channel frequency class (CFC) 60 Hz, as specified by SAE J211. They were then compensated for cross talk, inertially compensated using the corresponding accelerations, and zeroed. For the relaxed volunteer tests and all ATD tests, the data were zeroed using the average value during the pre-trigger period. For the braced volunteer tests, the data were zeroed using the average value during the pre-trigger period prior to pre-impact bracing.

For this study, only the normal forces (+ compression) for each reaction surface were analyzed since these forces corresponded to the primary loading direction for each reaction surface. The analyses focused on the time window corresponding to the occupants' initial inertial responses to the sled pulse. This was generally limited to a time window from 0.18 seconds (i.e., the beginning of the sled pulse) to 0.4-0.5 seconds for the 1 g tests, and from 0.18 seconds to 0.3-0.4 seconds for the 2.5 g tests. Average peak normal forces were calculated for each reaction surface using the local extrema (minimum or maximum) during this time window, and were compared between the THOR-AV-5F and relaxed and braced female volunteers for each test condition. The overall shape and timing of the force-time histories were also compared qualitatively between surrogates over the time window corresponding to the occupants' initial inertial responses to the sled pulse.

Volunteer and ATD Accelerations: Volunteer and ATD accelerations were filtered at CFC 60 Hz and converted to the SAE J211 coordinate system. Pre-test pictures were used to transform the volunteer head accelerations from the mouthpiece location to the approximate head CG location. Resultant accelerations were calculated for the head (volunteer head CG and THOR-AV-5F head CG) and neck (volunteer C7 and ATD T1) accelerations. Sternum accelerations were reported only in the x-direction (volunteer suprasternal notch and ATD mid-sternum).

Average peak accelerations were calculated for the head, neck, and sternum using the local extrema during the time window corresponding to the occupants' initial inertial response to the sled pulse. For the head and neck, average peak resultant accelerations were calculated as the maximum acceleration during this time window. For the sternum, average peak accelerations in the x-direction were calculated as the minimum acceleration during this time window. Average peak accelerations were compared between the THOR-AV-5F and relaxed and braced female volunteers for each test condition. The overall shape and timing of the acceleration-time histories were compared also qualitatively between surrogates over the time window corresponding to the occupants' initial inertial response to the sled pulses.

RESULTS

Reaction Forces

The THOR-AV-5F average peak normal forces were overall more similar to the relaxed volunteers than to the braced volunteers across all reaction surfaces and test conditions (Figure 7-Figure 8). Specifically, the THOR-AV-5F normal forces were closer in magnitude to those of the relaxed volunteers than the braced volunteers.

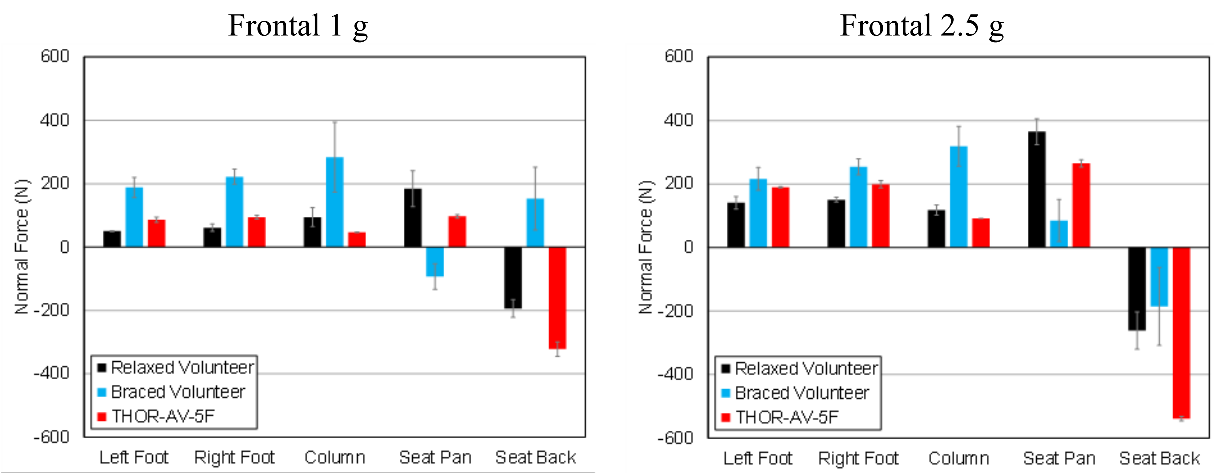

Figure 7: Average peak normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

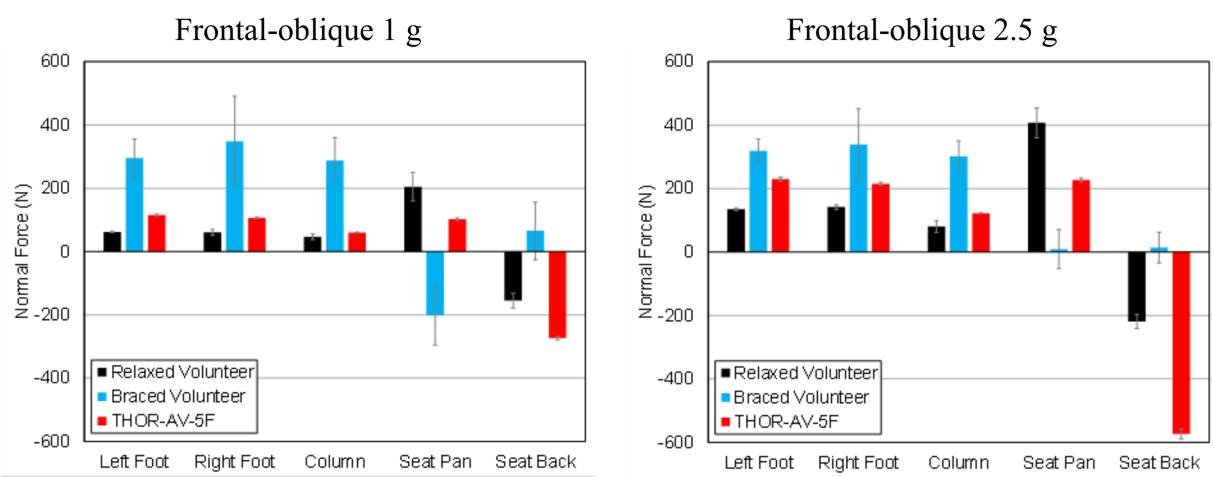

Figure 8: Average peak normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Foot Pedals: The THOR-AV-5F foot pedal forces were higher than the relaxed volunteers across all test conditions, with smaller differences observed for the 1 g tests and larger differences observed for the 2.5 g tests (Figure 7-Figure 12). The THOR-AV-5F foot pedal forces were lower than the braced volunteers across all test conditions, with the largest differences observed for the frontal-oblique 1 g test condition and the smallest differences observed for the frontal 2.5 g test condition (Figure 7-Figure 12). Qualitatively, the THOR-AV-5F foot pedal forces generally matched the relaxed volunteers during the initial loading phase of the 2.5 g tests in terms of shape and timing (Figure 9-Figure 12).

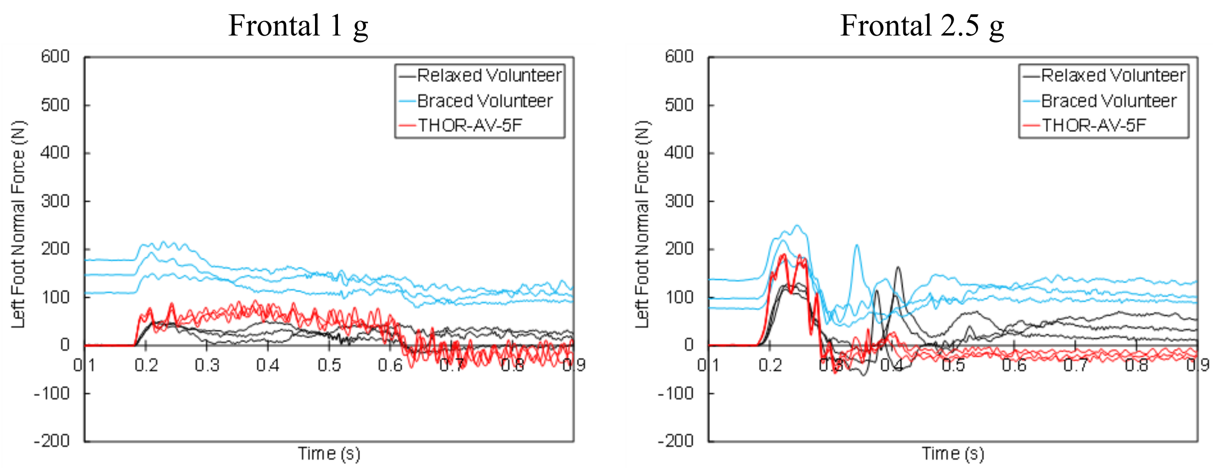

Figure 9: Left foot normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

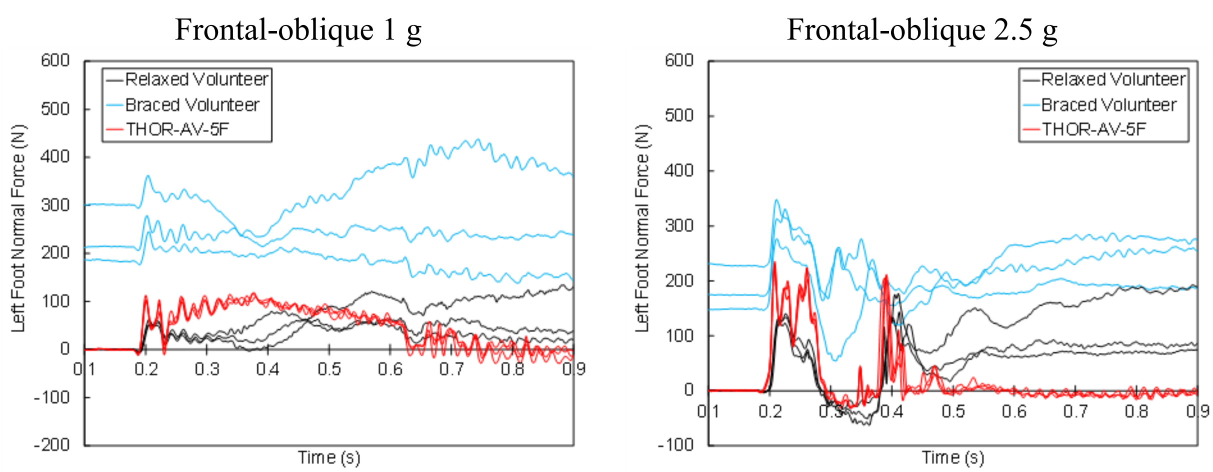

Figure 10: Left foot normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

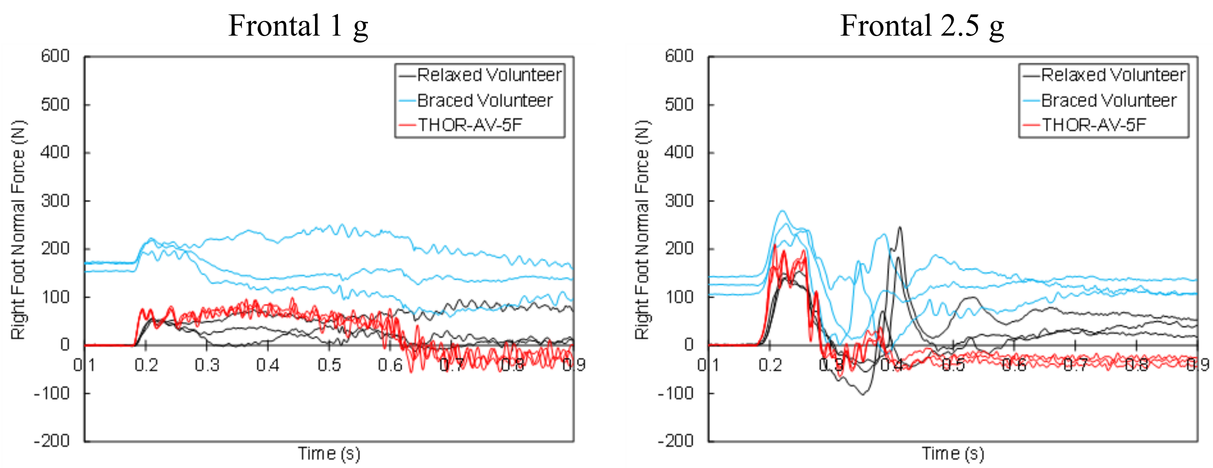

Figure 11: Right foot normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

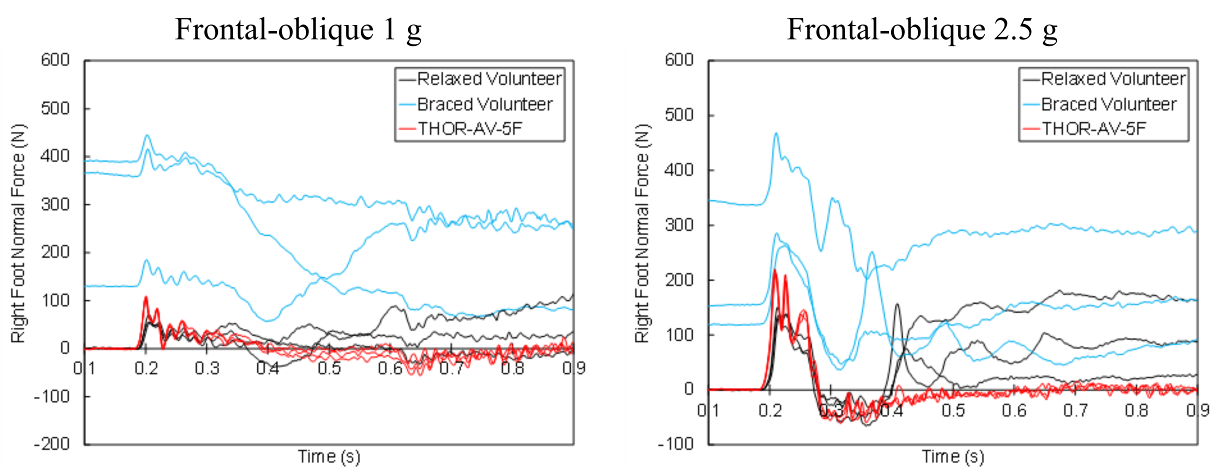

Figure 12: Right foot normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Steering Column: The THOR-AV-5F column forces were generally similar to the relaxed volunteers, with minimal differences across all test conditions (Figure 7-Figure 8, Figure 13-Figure 14). For the frontal tests, the THOR-AV-5F column forces were slightly lower compared to the relaxed volunteers (Figure 7, Figure 13). For the frontal-oblique tests, the THOR-AV-5F column forces were slightly higher compared to the relaxed volunteers (Figure 8, Figure 14). Compared to the braced volunteers, the THOR-AV-5F column forces were considerably lower across all test conditions (Figure 7-Figure 8, Figure 13-Figure 14). Qualitatively, the THOR-AV-5F column forces did not show strong similarities to the volunteer column forces in terms of overall shape and timing (Figure 13-Figure 14).

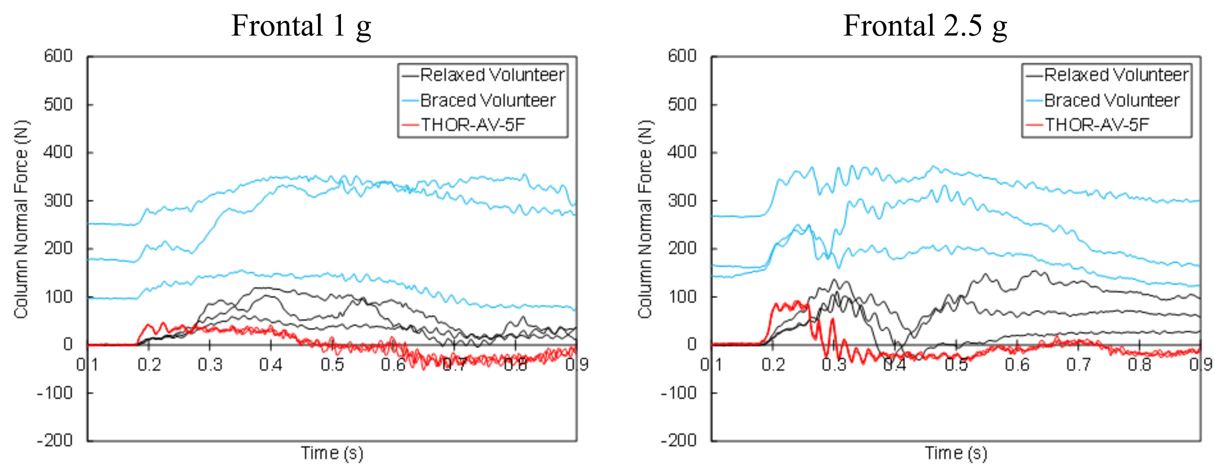

Figure 13: Steering column normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

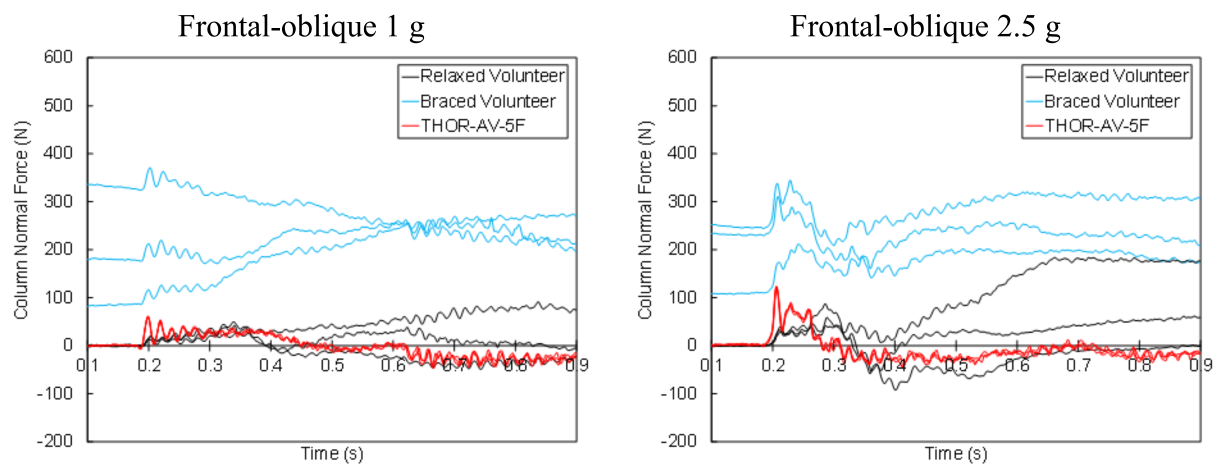

Figure 14: Steering column normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Seat Pan: Across all test conditions, the THOR-AV-5F seat pan forces were lower than the relaxed volunteers and higher than the braced volunteers (Figure 7-Figure 8, Figure 15-Figure 16). Comparing between the THOR-AV-5F and relaxed volunteers, smaller differences in seat pan forces were observed for the 1 g tests and larger differences were observed for the 2.5 g tests (Figure 7-Figure 8, Figure 15-Figure 16). Qualitatively, the THOR-AV-5F seat pan forces showed some similarities to the relaxed volunteers during initial loading phase of the frontal 2.5 g test condition (Figure 15-Figure 16).

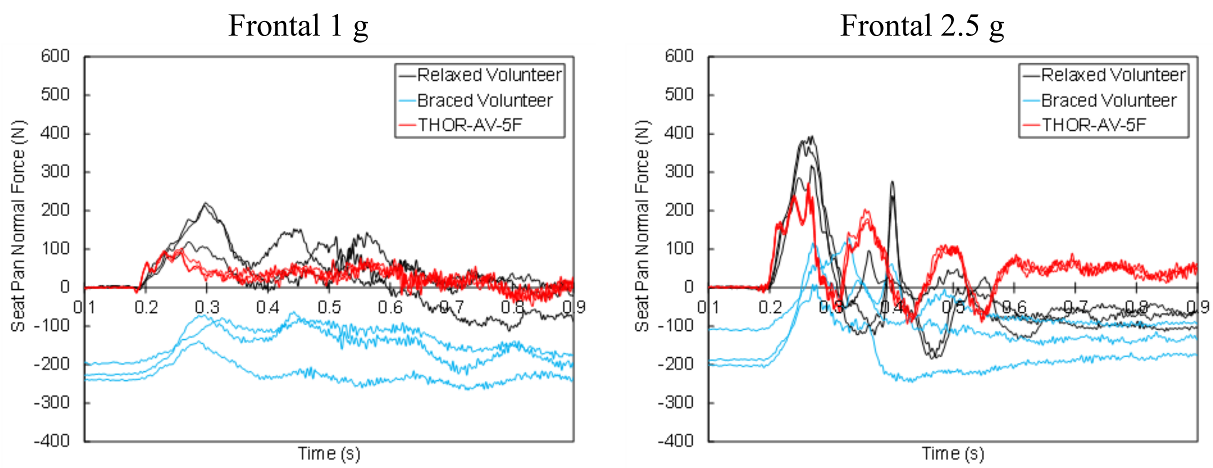

Figure 15: Seat pan normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

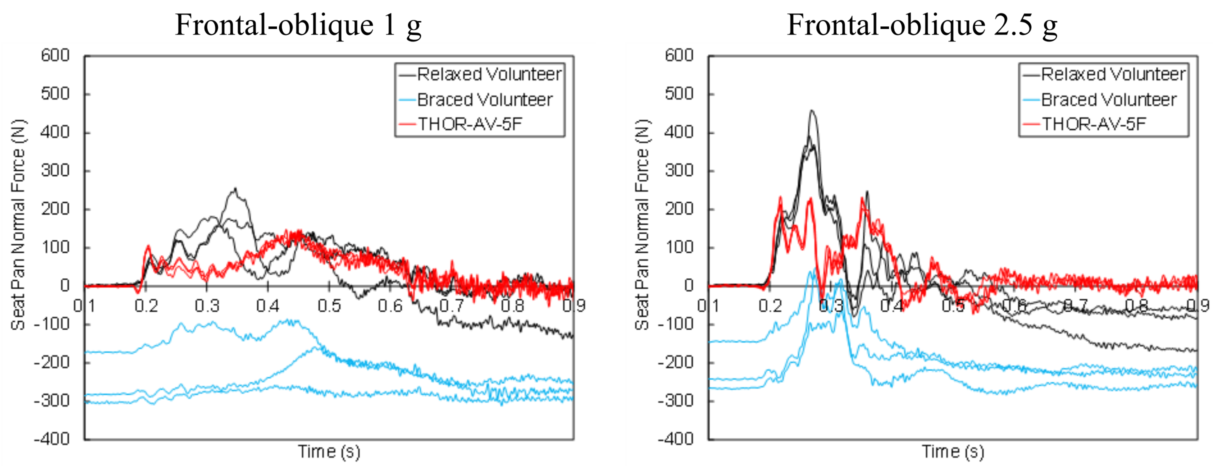

Figure 16: Seat pan normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Seat Back: Across all test conditions, the THOR-AV-5F seat back forces were lower than both the relaxed and braced volunteer seat back forces (Figure 7-Figure 8, Figure 17-Figure 18). The difference in seat back forces between the THOR-AV-5F and relaxed volunteers was greater for the 2.5 g tests compared to the 1 g tests (Figure 7-Figure 8, Figure 17-Figure 18). The difference in seat back forces between the THOR-AV-5F and braced volunteers was considerably greater than for the THOR-AV-5F and relaxed volunteers, particularly for the frontal-oblique 2.5 g test condition (Figure 7-Figure 8, Figure 17-Figure 18). Qualitatively, the THOR-AV-5F seat back forces showed some similarities to the relaxed volunteers during the initial loading phase of the 1 g tests (Figure 17-Figure 18).

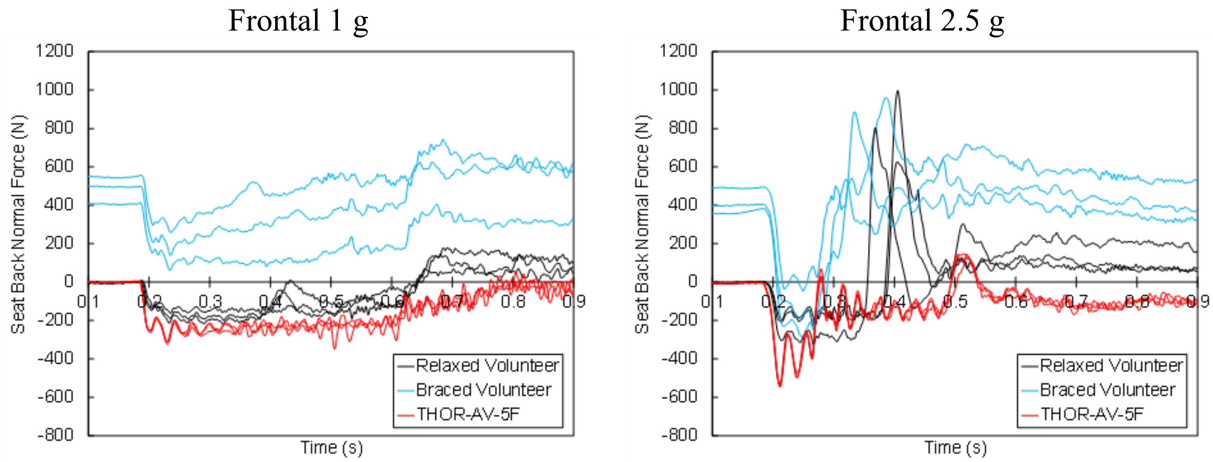

Figure 17: Seat back normal forces during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

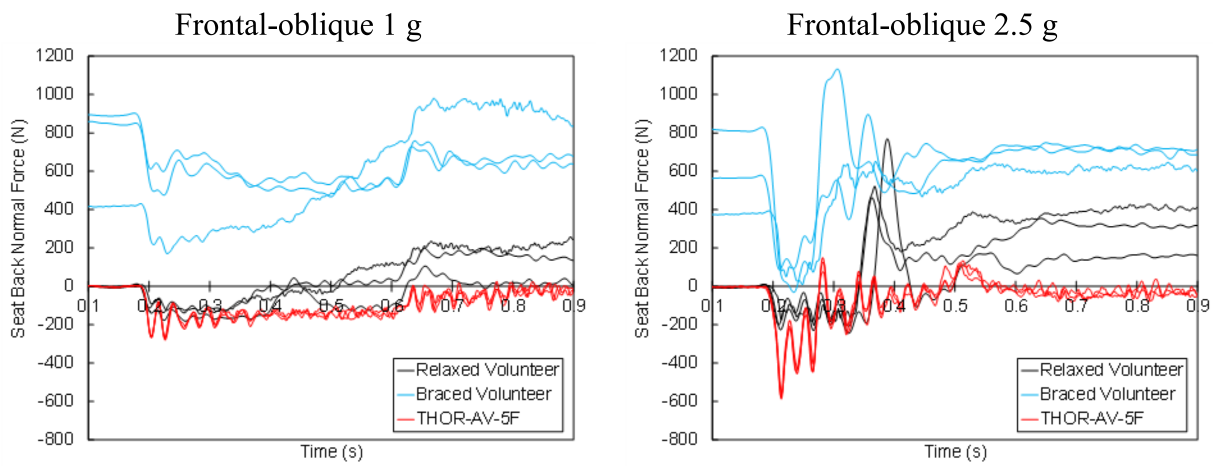

Figure 18: Seat back normal forces during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Volunteer and ATD Accelerations

The THOR-AV-5F average peak accelerations for the head, neck, and sternum were overall more similar to the relaxed volunteers compared to the braced volunteers across all test conditions (Figure 19-Figure 20). Observed differences in average peak accelerations between the THOR-AV-5F and relaxed volunteers were minimal, while observed differences between the THOR-AV-5F and braced volunteers were greater but still relatively small.

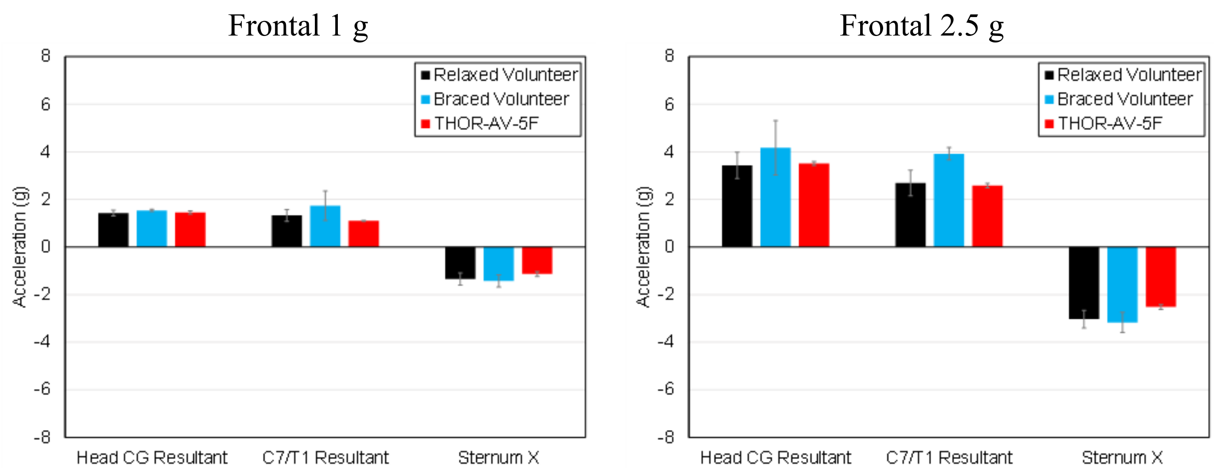

Figure 19: Average peak accelerations during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

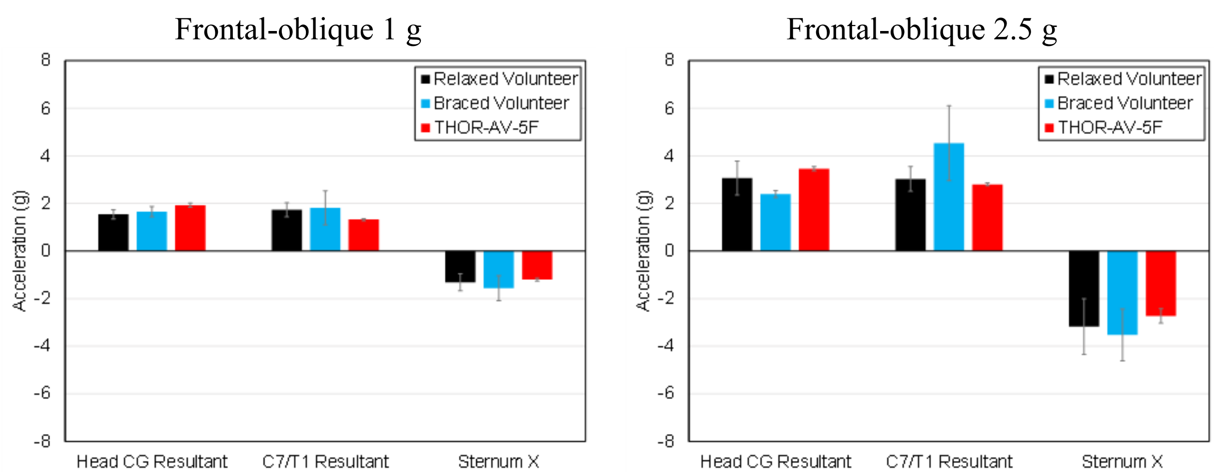

Figure 20: Average peak accelerations during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Head: The THOR-AV-5F head accelerations were similar to both the relaxed and braced volunteer head accelerations for the 1 g tests in terms of average peak resultant accelerations and overall qualitative shape and timing (Figure 19-Figure 22). For the 2.5 g tests, the THOR-AV-5F and relaxed volunteer head accelerations were also similar in terms of average peak resultant accelerations and qualitative shape and timing during the initial loading phase (Figure 19-Figure 22). Compared to the braced volunteers for the 2.5 g tests, the THOR-AV-5F head accelerations were lower in the frontal orientation and higher in the frontal-oblique orientation (Figure 19-Figure 22).

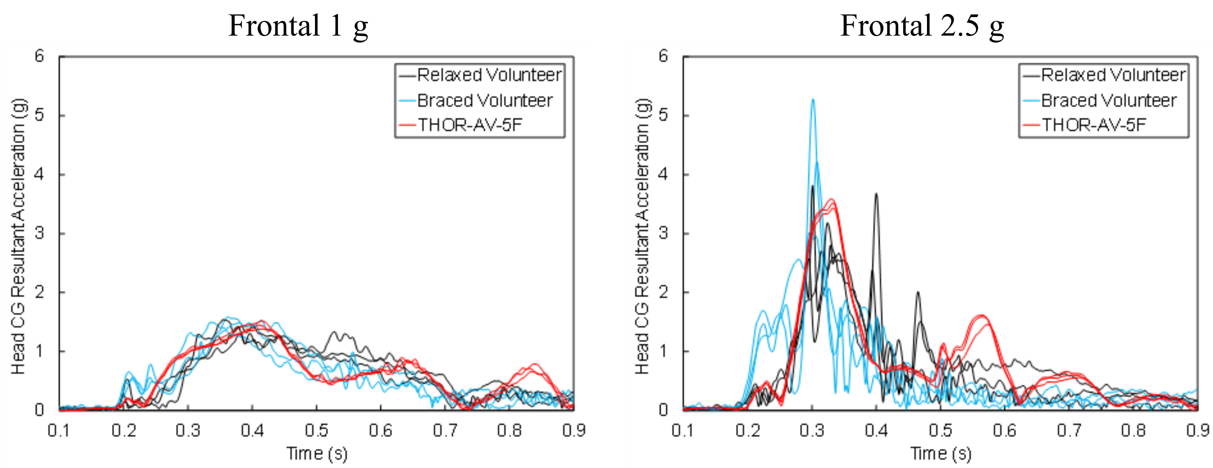

Figure 21: Head resultant accelerations during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

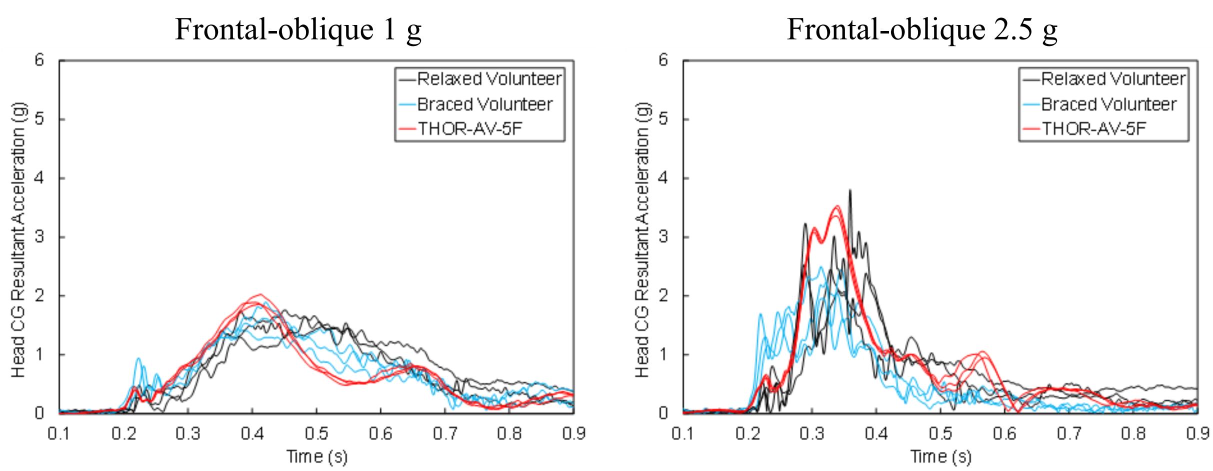

Figure 22: Head resultant accelerations during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Neck: The THOR-AV-5F neck accelerations were generally similar to the relaxed volunteers across all test conditions (Figure 19-Figure 20, Figure 23-Figure 24). Compared to the braced volunteers, the THOR-AV-5F had lower neck accelerations with greater differences observed for the 2.5 g tests than the 1 g tests (Figure 19-Figure 20, Figure 23-Figure 24). Qualitatively, the THOR-AV-5F neck accelerations generally matched the relaxed volunteers across all test conditions in terms of shape and timing during the initial loading phase (Figure 23-Figure 24).

Figure 23: Neck resultant accelerations during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

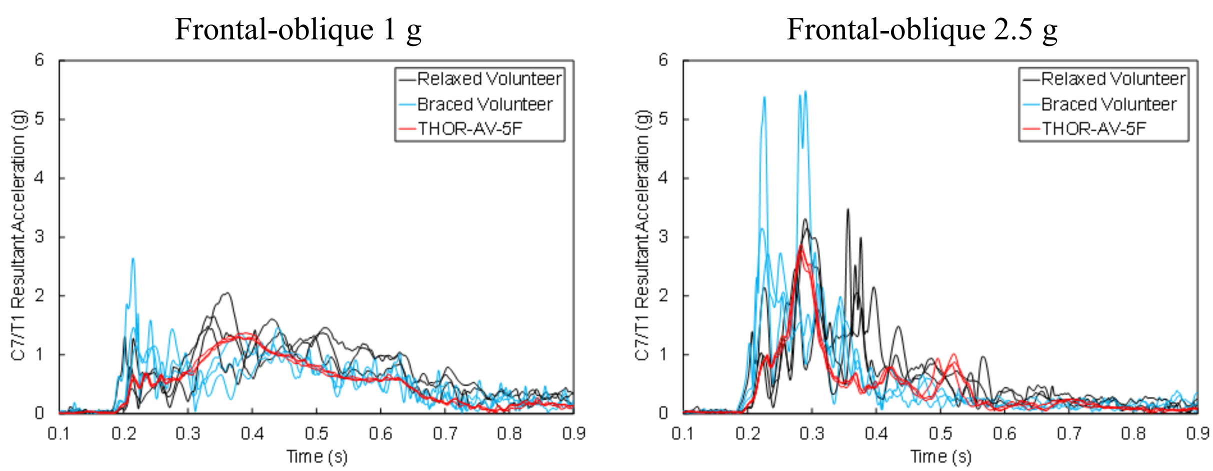

Figure 24: Neck resultant accelerations during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

Sternum: For the 1 g tests, the THOR-AV-5F sternum accelerations were generally similar to the relaxed volunteers and had minimal differences compared to the braced volunteers (Figure 19-Figure 20, Figure 25-Figure 26). For the 2.5 g tests, the THOR-AV-5F sternum accelerations were smaller than both the relaxed and braced volunteers, with minimal differences compared to the relaxed volunteers and more considerable differences compared to the braced volunteers (Figure 19-Figure 20, Figure 25-Figure 26). Qualitatively, the THOR-AV-5F sternum accelerations more closely matched the relaxed volunteers compared to the braced volunteers across all test conditions in terms of shape and timing during the initial loading phase (Figure 25-Figure 26).

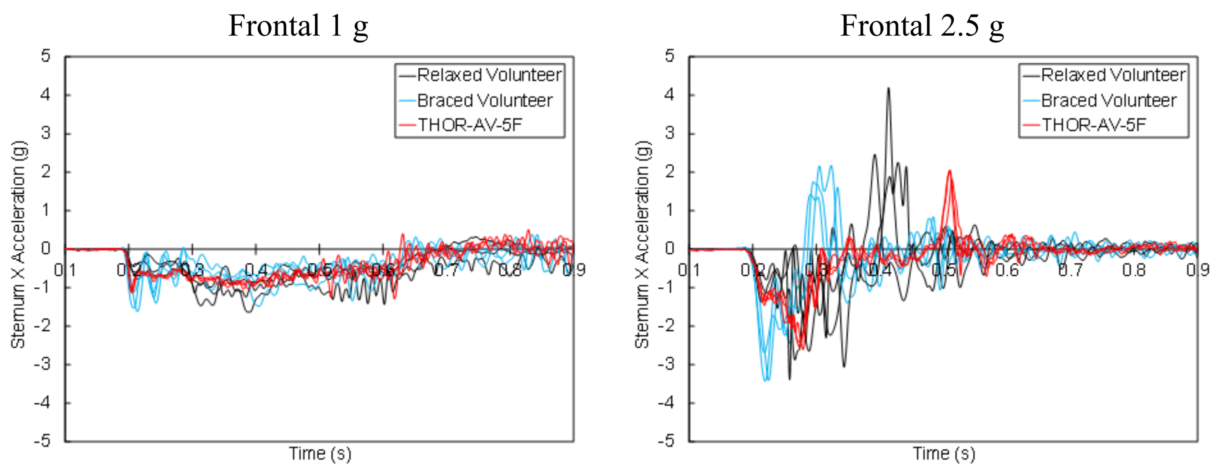

Figure 25: Sternum x-direction accelerations during the frontal tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

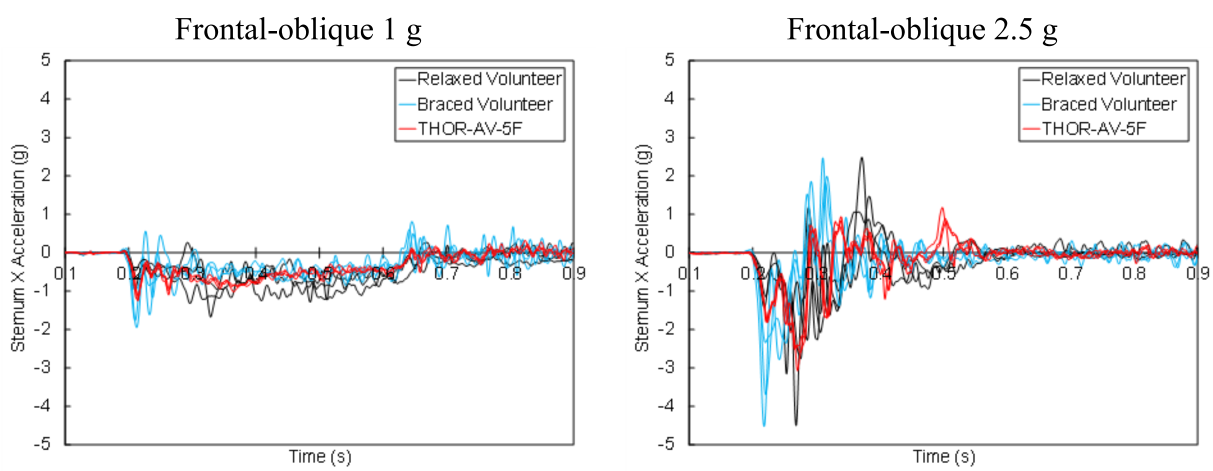

Figure 26: Sternum x-direction accelerations during the frontal-oblique tests for the THOR-AV-5F, relaxed volunteers, and braced volunteers.

DISCUSSION

Overall, the THOR-AV-5F reaction forces and accelerations were more similar to the relaxed volunteers compared to the braced volunteers across all test conditions. The observed trends indicate that the THOR-AV-5F was more able to match the response of a relaxed female volunteer compared to a braced female volunteer during low-speed sled tests. As such, the THOR-AV-5F may be capable of capturing some aspects of a live human response, assuming the occupant is completely relaxed and in an unaware state during an autonomous braking event or impending low-severity crash. The analyses presented here indicate that the THOR-AV-5F generally cannot capture a live human response when the occupant is completely braced and aware of an impending crash. This further emphasizes the important role that muscle activation plays in occupant response during pre-crash braking and low-severity crash events, and how current ATDs are not capable of capturing this accurately.

However, using ATDs to assess and predict occupant response during low-severity events may still provide valuable information. The THOR-AV-5F response was generally in between the relaxed volunteer response and the braced volunteer response in this study and may represent an intermediate response. It is likely that occupants in real world scenarios are more likely to respond in a manner in between the two volunteer muscle condition extrema evaluated in this study. Similar observations were made in previous studies that quantified the kinematic and kinetic responses of the Hybrid III 50th percentile male ATD and relaxed and braced 50th percentile male volunteers during low severity frontal sled tests (2.5 g and 5 g) (Beeman et al., 2012, 2015). The ATD exhibited an intermediate response that was in between the relaxed volunteer and braced volunteer responses. Specifically, the ATD average peak forward excursions were more similar to the braced volunteers, but the ATD reaction forces were more similar to the relaxed volunteers.

It should be noted that the THOR-AV-5F was not specifically designed to assess occupant safety during low-severity crash scenarios. Previous studies have assessed the biofidelity of various ATDs in impact scenarios that the ATDs were not designed to be used in. For example, the Hybrid III, designed for use in high-severity frontal impacts, was tested in low-speed rear impacts (4 g) and was found to have considerable differences in occupant response compared to volunteers (Yaguchi et al. 2006), (Yamazaki et al., 2008). However, the Hybrid III head kinematics were found to have some similarities to volunteers when tested in low-speed lateral impacts (2.5 g and 4 g) (Parenteau et al., 2002). This indicates that the biofidelity of ATDs varies when used in impact scenarios they were not designed for, so this practice must be done with careful consideration. Although the THOR-AV-5F was not designed to accurately capture the live human response during low-severity events, it may have been able to capture some aspects of the relaxed volunteer response in this study because of its design improvements from previous iterations (i.e., improved neck design).

It is important to assess how the THOR-AV-5F performs during low-severity events, as these scenarios will likely become increasingly common with the prevalence of crash avoidance technology in new (autonomous) vehicles. Crash avoidance technologies like AEB can displace occupants out of position during a pre-crash braking event when the vehicle decelerates. Moving out of position prior to impact can influence the effectiveness of vehicle safety systems in a subsequent crash event. Therefore, it advantageous to develop ATDs that can be used to quantify and understand occupant responses during both pre-crash and crash events. Performing matched volunteer and ATD sled tests for small females in particular is also important because females represent a vulnerable occupant population with increased injury risks during vehicle crashes.

Limitations and Future Work

The quantitative comparisons in reaction forces and accelerations between volunteers and ATDs in these analyses were limited to average peak normal forces and average peak accelerations. These comparisons, along with qualitative observations with respect to the shape and timing of the time histories, were limited to the occupants' initial loading phase. Significant differences were not assessed using statistical analyses or other methods to determine meaningful differences between surrogates. More robust comparisons could be made by developing volunteer occupant response corridors and using an objective rating metric to determine how well the ATD response matches the volunteer responses. These methods will be used in future analyses that will also quantify volunteer and ATD excursions, belt loads, and belt spool out.

The work presented here is part of a larger ongoing study, focused on quantifying the occupant kinematic, kinetic, and muscle activation responses of 20 relaxed and braced volunteers (ten 5th percentile females and ten 50th percentile males) during low-speed frontal and frontal-oblique sled tests (Chan et al. 2021a, 2021b, 2022). Additional testing is also planned to quantify and compare the occupant response of the THOR-AV-50M ATD to analogous 50th percentile male volunteers during matched sled tests.

CONCLUSIONS

This is the first study to quantify the occupant response of the THOR-AV-5F ATD during low-speed frontal and frontal oblique sled tests, and compare the ATD response to relaxed and braced 5th percentile female volunteer responses during matched tests. Overall, the THOR-AV-5F reaction forces and accelerations exhibited some differences compared to the volunteers, but were generally more similar to the relaxed volunteers than to the braced volunteers across all test conditions.

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