Comparison of WorldSID and Cadaver Responses in Low-Speed and High-Speed Nearside Impact

Jonathan D. Rupp, Carl S. Miller, Matthew P. Reed, Kathleen D. Klinich, and Lawrence W. Schneider
University of Michigan Transportation Research Institute
United States of America

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ABSTRACT

A series of lateral impact tests was performed in which the WorldSID midsize-male crash-test dummy was struck with a segmented padded impactor that separately loaded the thorax, abdomen, iliac wing, greater trochanter, and mid thigh. Tests were conducted using 8 m/s and 3 m/s initial impact velocities with velocity histories that mimic those produced in staged side-impact tests. A 5.1-cm abdomen offset was used to produce similar loading conditions as were used in a recently reported set of side-impact tests performed using seven male cadavers.

WorldSID thorax, abdomen, iliac crest, pelvis, and mid thigh forces, internal/external deflections, and pelvis accelerations were compared to ±1SD corridors developed from the 3-m/s and 8-m/s cadaver responses. Results of these comparisons indicate that the WorldSID abdomen produces impact forces that are higher than the associated cadaver response corridor and external deflections that are lower than the associated response corridor for both the 3 m/s and 8 m/s loading conditions, suggesting that the abdomen rib stiffness should be reduced. Greater-trochanter and iliac-wing forces in 3-m/s tests were within, or slightly above, response corridors while these same measurements were substantially above response corridors for the 8-m/s tests. Lateral accelerations of the pelvis in the 3-m/s tests were slightly above target response corridors while lateral pelvic accelerations in the 8-m/s tests were within target response corridors. The combination of these results suggest that the WorldSID pelvis is too stiff and has too much tightly coupled mass.

INTRODUCTION

The responses of the WorldSID midsize male crash-test dummy thorax, abdomen, and pelvis are based on tests in which whole cadavers were dropped onto rigid plates, decelerated into rigid and padded segmented impactors, and impacted using ballistic masses (ISO TR9790). Although these tests have provided seminal data on lateral impact response, they have several important limitations, including not providing usable data on abdomen force-deflection characteristics and not independently measuring iliac crest and greater trochanteric responses during whole-body side-impact tests. Further, most previous whole-body side impact sled tests used a single-size load wall for different sized subjects and, as a result, produced response data for the thorax, abdomen, and pelvis that are confounded with responses of adjacent body regions. Lastly, the lowest impact velocity used in the side-impact sled tests used to develop WorldSID was 6.7 m/s, which is well above some door-to-crash-test-dummy initial impact velocities in FMVSS 214 tests. Further, as vehicle side structures improve and side-impact airbags are phased into the vehicle fleet, the velocities at which the intruding side structures load the dummy in FMVSS 214 and other side-impact tests is likely to decrease. For these reasons, there is a need to characterize human impact response for low-speed nearside impact conditions using non-rigid impact surfaces.

To address this need, a series of side-impact tests was performed with seven whole cadavers using a sled-to-sled side-impact test facility (Miller and Rupp 2011). A padded segmented "impact wall" with a 5.1-cm abdomen offset attached to one sled was used to separately load the thorax, abdomen, iliac wing, greater trochanter, and thigh of a subject seated on the other sled. Sizes and locations of the impactor segments used to load different parts of the body were scaled with subject anatomy so the same anatomic regions were loaded in tests of different sized cadavers. Cadavers were impacted on one side of the body with an initial loading velocity of 3 m/s and on the contralateral side with an initial loading velocity of 8 m/s. These impact velocities represent the lowest and mean±1SD door velocities at the time of crash-dummy contact measured in a series of SNCAP moving-deformable-barrier tests of passenger cars performed between 1998 and 2005. CT scans of the cadavers were performed before and after the 3-m/s test to verify that rib fractures were not pre existing or produced by the low-speed test. Fifty-nine channel chestbands were used to measure deformation histories of the thorax and abdomen during impact loading. Responses from these tests were normalized to midsize-male anthropometry and used to generate ±1SD corridors using the methods described by Maltese et al. (2002).

This paper describes a series of lateral impact tests that were conducted to evaluate the response of the WorldSID midsize-male crash test dummy relative to 3-m/s and 8-m/s corridors reported by Miller and Rupp (2011).

METHODS

Similar to cadaver tests, the WorldSID (WSID) tests were performed using a custom-designed dual-sled impact facility consisting of a 725-kg impactor sled with a set of padded impactor surfaces that represent a generic door interior, and a second 360-kg occupant sled with the WISD positioned facing lateral to the direction of impactor loading.   A rendering of this test facility is shown in Figure 1.

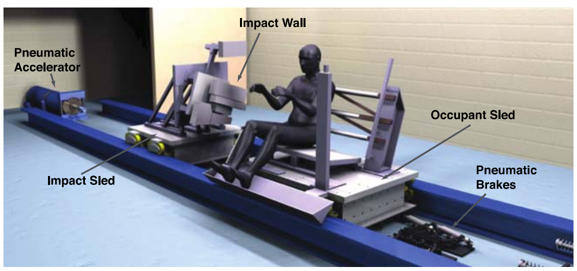

Figure 1. Rendering of the custom-designed dual-sled impact facility used for cadaver and WorldSID side-impact testing.

The process for conducting a test involved using a pneumatic accelerator to accelerate the impactor sled to a pre-impact velocity of 3 m/s, 8 m/s, or 10 m/s. The first two velocities are the same as those used by Miller and Rupp (2011) to develop cadaver response corridors. The 10-m/s test velocity was selected because an ongoing series of side-impact cadaver tests will provide additional data that can be used to develop response corridors at this impact velocity. After reaching the target pre-impact velocity, the impactor sled contacted energy absorbing material on the occupant sled. The timing of this impact was set so that it occurred at the same time that the impactor contacted the WorldSID in the 8-m/s and 10-m/s tests. In the 3-m/s tests, the impactor contacted the WorldSID before the impactor sled contacted the occupant sled. For the 10-m/s and 8-m/s tests, aluminum honeycomb was used as the energy absorbing material to produce the desired impactor velocity profiles determined from analysis of a series of 1999-2005 NCAP side-impact tests (Miller and Rupp 2011). Figure 2 compares the impactor sled velocity profiles for the 10-m/s, 8-m/s and 3-m/s tests to mean ± 1 SD corridors of door velocities reported by Rupp and Miller (2011), and shows the timing of impactor and occupant sled contact for the three impact velocities. Note that tzero in Figure 2 is the time of WorldSID contact.

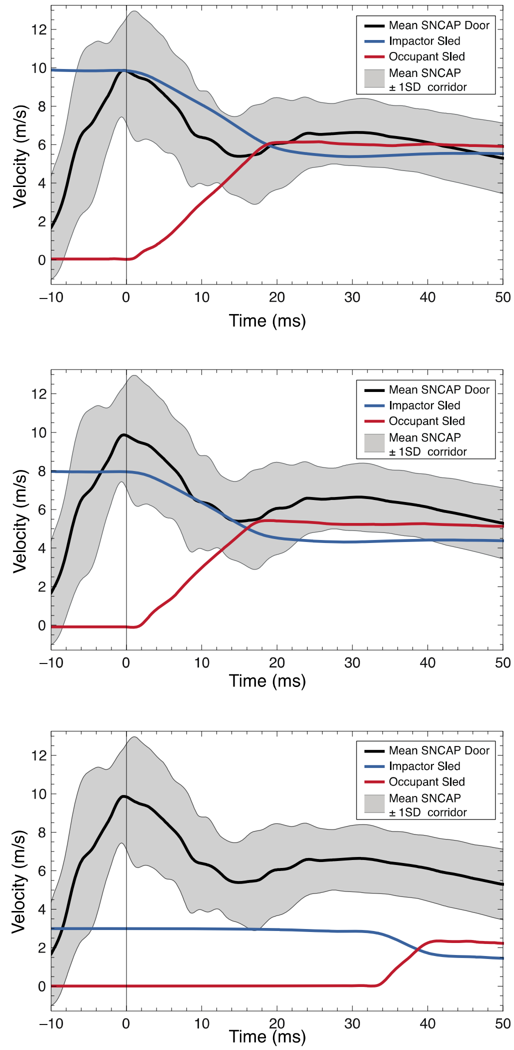

Figure 2. Comparison of impactor and occupant sled velocities to mean ±1 SD SNCAP door velocity-time corridors for the 10-m/s (top), 8-m/s (middle), and 3-m/s (bottom) dual-sled tests.

The impact “wall” was segmented to allow independent measurement of loads applied to the thorax, abdomen, iliac wing, greater trochanter, and mid thigh. The positions and sizes of the load plates were set so that the plates contacted parts of the WorldSID corresponding to the body regions that were loaded in the cadaver tests. Forces applied to each of the body region were measured by load cells connected to 12.7-mm thick aluminum plates, and were inertially compensated using accelerometers attached to each loading plate. Each plate was covered with 80-mm thick blocks of Microcell 1900 foam (72 kPa). The deflection of each block of foam was measured by a linear potentiometer that was mounted to the posterior surface of the load-cell plate with the end of the moving shaft connected to the anterior surface of the foam. This particular type of foam was selected because, as shown in Figure 3, when this foam was used in a series of pilot tests conducted using a SID Hybrid III in the 10 m/s impact condition, it resulted in pelvis and lower spine accelerations that were similar to those measured in the SNCAP tests from which the door velocity corridors were derived. In addition, cyclic compression testing where a block of the foam was repeatedly compressed to 20% of its pre-deformed height resulted in no change in force-deflection characteristics.

The WorldSID test matrix is shown in Table 1. Data and videos from all tests are available in the NHTSA biomechanics database, as are force-deflection characteristics of the foam padding used on the impactor surfaces. The abdomen, thorax, and pelvic responses of the WorldSID were calibrated before, in the middle of, and after the end of the test series. No body regions were found to be out of calibration in any of the calibration tests.

Table 1. WorldSID Test Matrix

Impactor Velocity (m/s)	Chestband Location	Test IDs (NBAW10XX)
3	None	07, 08, 25, 26
3	Thorax	30
3	Abdomen	15, 27
8	None	09, 10, 17, 20
8	Thorax	29
8	Abd.	16, 28
10	Abdomen	13, 14, 18, 19

All WorldSID tests used an impactor configuration in which the plate that loaded the abdomen was offset 5.1 cm towards the WorldSID from the other portions of the impactor, as shown in the illustration of Figure 4. A separate series of abdomen-plus-pelvis-offset tests was performed so that WorldSID responses can be compared to responses measured in an ongoing series of cadaver tests that uses an abdomen-plus-pelvis offset.

In a subset of ten tests, the external deflection of the thoracic and abdomen regions of the WorldSID were measured using a single 59-channel chestband. Separate tests were conducted to measure external abdomen versus the external thorax deflections due to the limited number of available data-acquisition channels.

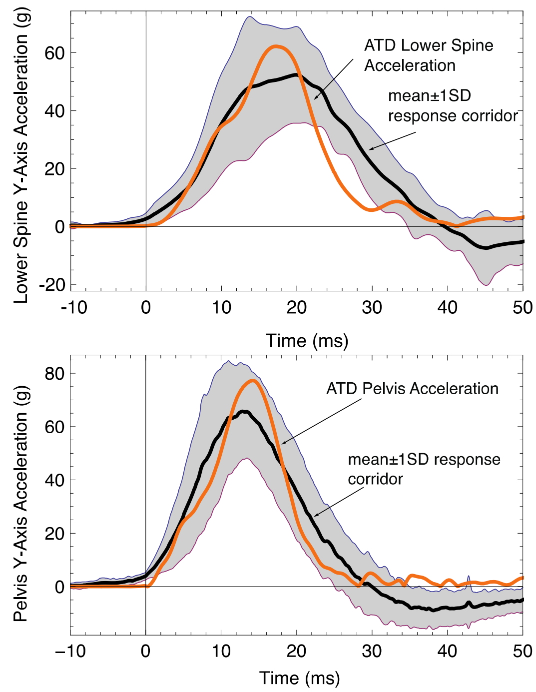

Figure 3. Comparison of WorldSID lower-spine (top) and pelvis (bottom) acceleration histories produced during a 10-m/s sled-to-sled impact to ± 1 SD response corridors developed from analysis of SNCAP data measured by a SID Hybrid III.

Images of the WorldSID configured for external thoracic and abdominal deflection measurements are shown in Figure 5. For tests where external thoracic deflection was measured, the chestband was wrapped around the exterior of the WorldSID at a level corresponding with the second and third thoracic ribs and aligned with the approximate center of the thoracic loading plate. The ends of the chestband were overlapped and secured with tape to prevent changes in the circumference of the chestband during the impact event. The portion of the chestband aligned with the ATD spine was attached to the spine box to provide a fixed reference point. The setup for the abdomen chestband experiments was similar to the thoracic chestband tests except that the chestband was positioned around the WorldSID abdomen ribs 1 and 2 and aligned with the center of the abdomen loading plate.

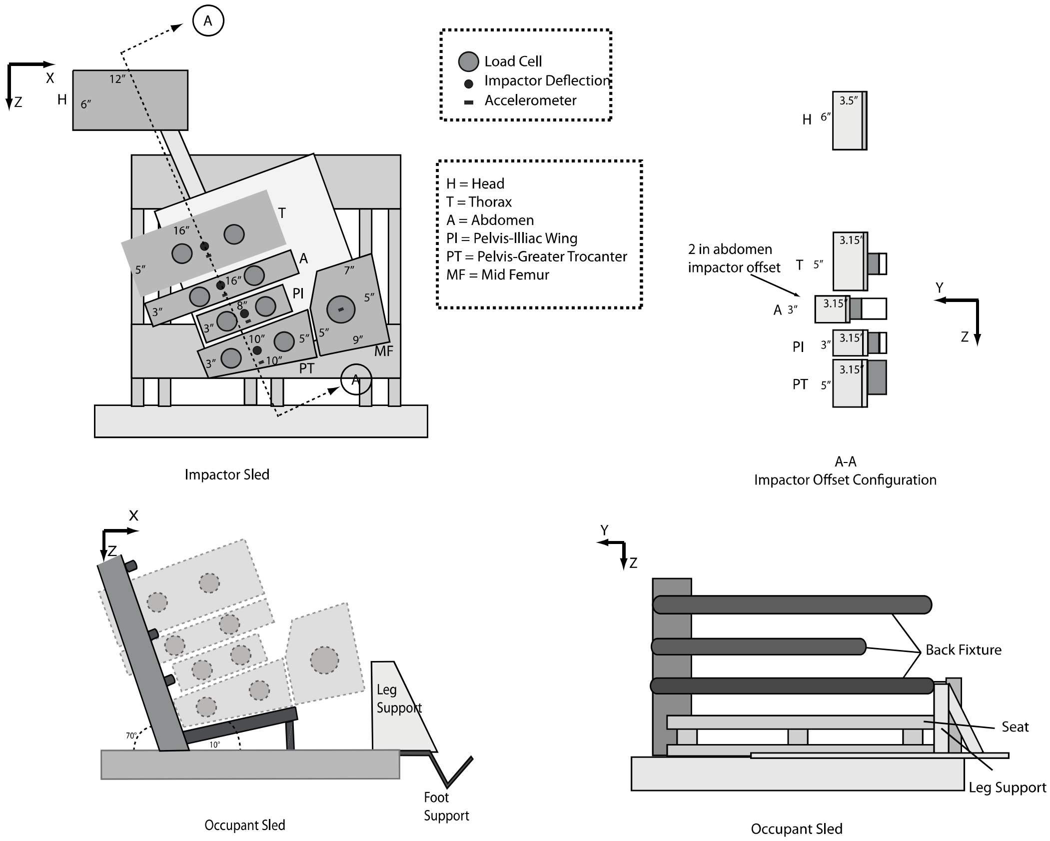

Figure 4. Illustration showing the configuration of the dual-sled door-shaped impactor on the impactor sled and the occupant sled.

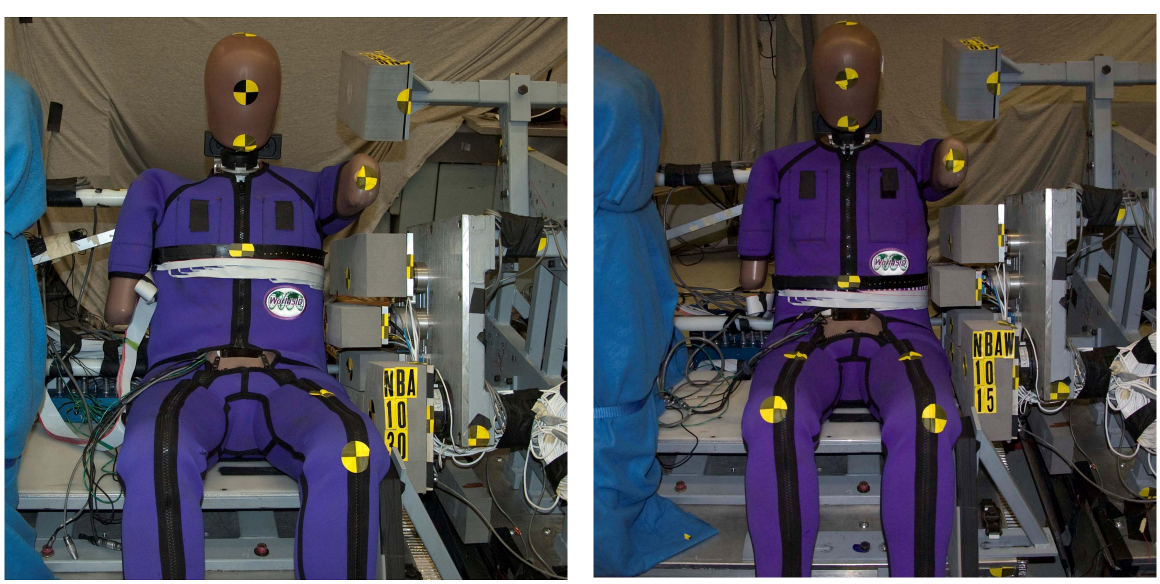

Figure 5. WorldSID configured for external thoracic (left) and abdominal (right) deflection measurements using the abdomen-offset impact condition and a single 59-channel chestband.

External deflections were calculated from chestband contours by using methods described by Pintar et al. (1997) and Maltese et al. (2002). These involve first defining a reference line connecting the point on the contour located at the spine and a point corresponding to the location of either the sternum or the anterior-most point on the abdomen. Next, vectors were defined that were perpendicular to these lines and passed through the lateral most points on the abdomen and thorax chestbands on the sides of the chestbands that interacted with the impactor. The change in the lengths of these vectors relative to their lengths at the time of impact impact were used to estimate half-thorax and half-abdomen deflection histories. Internal chest and abdomen deflections were calculated using measurements of rib motions made using IR-TRACCs.

RESULTS

Applied force histories at the five measured WorldSID regions (thorax, abdomen, iliac wing, greater trochanter, and mid thigh) as well as corresponding mean cadaver response and mean ± 1 SD response corridors for the 3-m/s and 8-m/s tests are shown in Figure . Mean peak applied forces for 3-m/s and 8-m/s tests are listed in Tables 2 and 3, respectively.

Table 2. Mean WorldSID and Cadaver Peak Applied Forces from 3-m/s Tests

	Applied Force	
Body Region	WorldSID (kN)	Cadaver (kN)
Thorax	1.2	1.3
Abdomen	1.9	1.5
Iliac Wing	0.74	0.73
Greater Trochanter	1.6	1.4
Mid thigh	2.1	1.5

Table 3. Mean WorldSID and Cadaver Peak Applied Forces from 8-m/s Tests

	Applied Force	
Body Region	WorldSID (kN)	Cadaver (kN)
Thorax	2.5	2.9
Abdomen	3.2	2.8
Iliac Wing	1.6	1.3
Greater Trochanter	3.1	2.2
Mid thigh	4.1	2.4

For both the 3-m/s and 8-m/s tests, the magnitudes of peak force applied to the WorldSID and cadaver thoraces are similar. However, for the 8-m/s tests, the shape of the WorldSID thoracic response differs from that of the cadaver. Applied abdominal forces are slightly higher for the WorldSID than the cadaver during both the 3- and 8-m/s tests, with the percent difference being greater during the 3-m/s tests. WorldSID iliac wing and greater trochanter peak forces are similar to the cadaver peak forces for the 3-m/s tests with the WorldSID peak force leading the cadaver peak force slightly. These peak forces are higher for the WorldSID than the cadaver for the 8-m/s tests. Mid-thigh peak forces are higher for the WorldSID for both the 3-m/s and 8-m/s tests, with the difference being greater during the 8-m/s tests.

Table 4. Peak WorldSID and Cadaver Pelvis Y-Axis Accelerations

	Pelvis y-axis Accelerations	
Test Condition	WorldSID (*g*)	Cadaver (*g*)
3 m/s	18	14
8 m/s	50	49

Pelvis y-axis accelerations for the WorldSID and cadaver are shown in Figure 7, and the mean peak values are listed in Table 4. WorldSID pelvis y-axis accelerations are slightly higher than the mean peak values for the cadaver for the 3-m/s tests, but are almost identical for the 8-m/s tests.

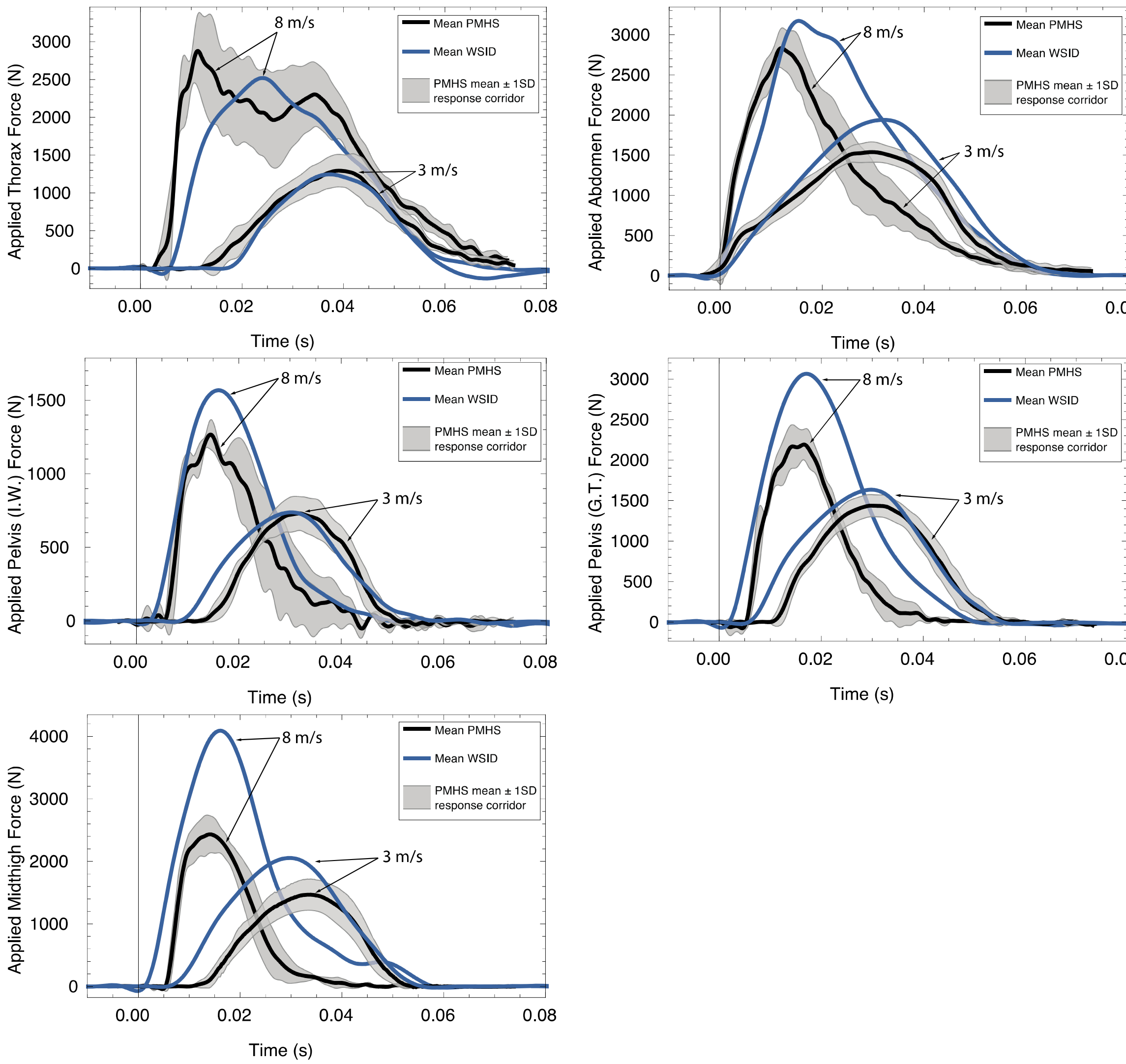

Figure 6. Applied force histories for the thoracic (top left), abdomen (top right), iliac wing (middle left), greater trochanter (middle right), and mid thigh (bottom left) for the 3- and 8-m/s tests.

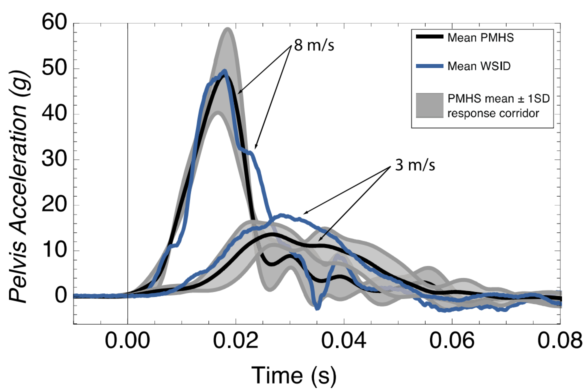

Figure 7. Comparison of WorldSID pelvis accelerations to mean ±1SD cadaver response corridors for 3-m/s and 8-m/s tests.

Figure 8 compares the WorldSID internal thoracic deflection measured by the IRTRACCs on the first and second thoracic ribs and chestband-measured WorldSID external thoracic deflection in the 3-m/s and 8-m/s tests to the associated cadaver corridors. Peak external thorax deflections for both the WorldSID and the cadaver are listed in Table 5. Chestband contours from the WorldSID thorax at the time of contact and at the time of peak deflection are shown in Figure 9 for both the 3-m/s and 8-m/s tests. Magnitudes of the external WorldSID deflections for both the 3-m/s and 8-m/s tests are less than the mean external deflection of the human cadaver for similar loading conditions.

Table 5. WorldSID and Cadaver Peak Internal and External Thoracic Deflections

	WorldSID		Cadaver
Test Condition	External (mm)	Internal (mm)	External (mm)
3 m/s	31	12, 10	47
8 m/s	44	27, 23	54

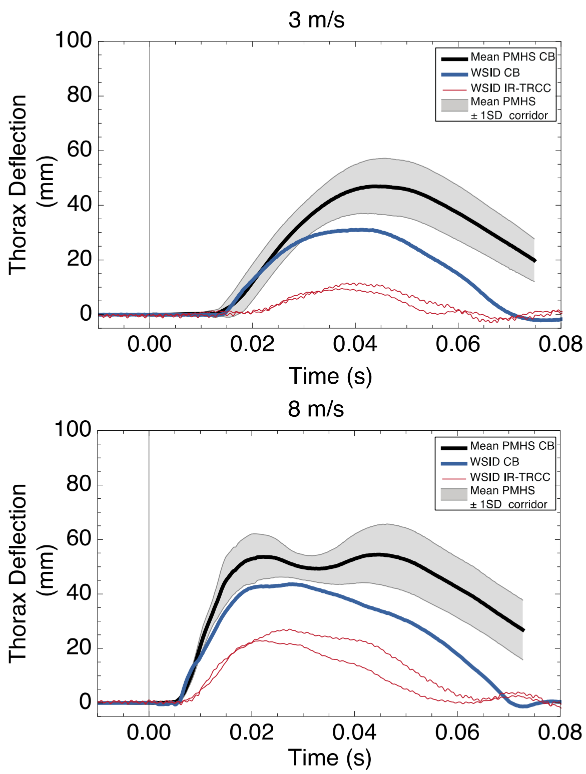

Figure 8. Comparison of mean cadaver and WorldSID thoracic deflection histories for the 3-m/s (top) and 8-m/s (bottom) tests.

Figure 10 compares WorldSID internal and external abdomen deflection histories measured in the 3-m/s and 8-m/s tests to the associated cadaver response corridors. External WorldSID deflections (blue line) and internal (red line) deflections of the first and second abdomen ribs are shown. Mean peak abdomen deflections for the WorldSID and cadaver tests are listed in Table 6. Peak values of the external WorldSID deflections for both the 3-m/s and 8-m/s tests are less than the mean peak external deflection of the human cadaver. The difference between peak external and internal WorldSID abdomen deflections is approximately 12 -13 mm, which is approximately equal to the thickness of the chest jacket.

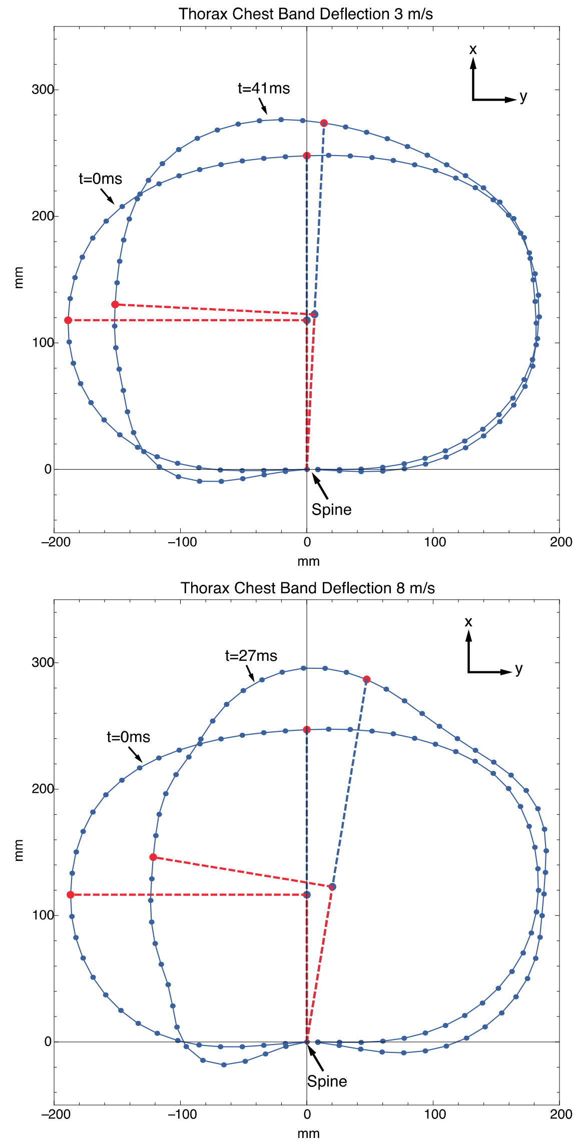

Figure 9. External WorldSID thorax chestband contours for the 3 m/s (top) and 8 m/s (bottom) at the time of abdomen contact and time of peak thorax deflection.

Table 6. WorldSID and Cadaver Peak Internal and External Abdomen Deflections

	WorldSID		**Cadaver**
Test Condition	**External (mm)**	**Internal (mm)**	**External (mm)**
3 m/s	29	18, 17	74
8 m/s	48	36, 35	75

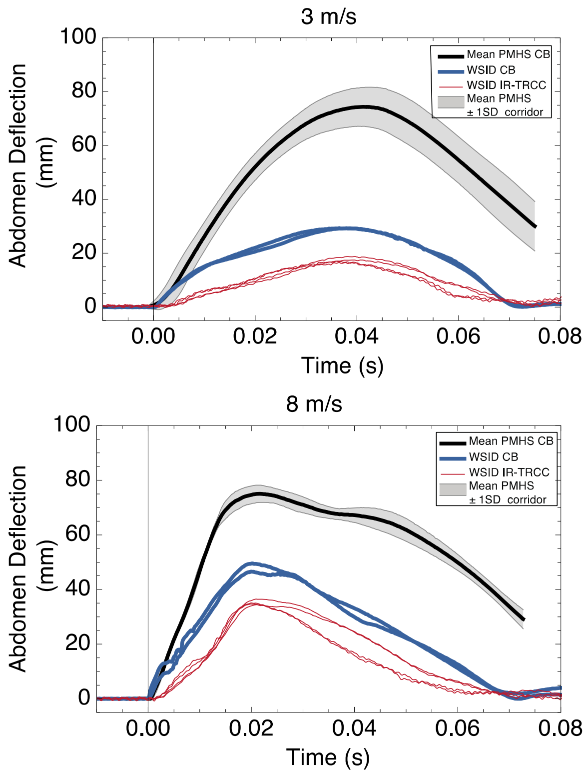

Figure 10. Comparison of internal and external abdomen deflection histories to cadaver abdomen deflection history corridor for the 3-m/s (top) and 8-m/s (bottom) tests.

Chestband contours of the external surface of the WorldSID abdomen at the time of loading and at the time of peak deflection are shown in Figure 11 for both the 3-and 8-m/s tests. External abdomen force-deflection responses from the WorldSID and cadaver tests at 3-m/s and 8-m/s are compared in Figure 12. WorldSID and cadaver external thoracic force-deflection responses from 3-m/s and 8-m/s tests are compared in Figure 13. In both cadaver and WorldSID force-deflection responses, there is force at zero deflection because abdomen and thorax impactor plates contacted parts of the abdomen and thorax before contacting the chestbands.

In general, the WorldSID abdomen is stiffer than the cadaver abdomen with the difference being greater for the 3-m/s tests than the 8-m/s tests. As indicated by Figure 6 and the force-deflection responses in Figure 10, this is primarily because the WorldSID abdomen does not deform as much as the cadaver abdomen under similar applied forces rather than the WorldSID abdomen producing higher impact forces than the cadaver abdomen.

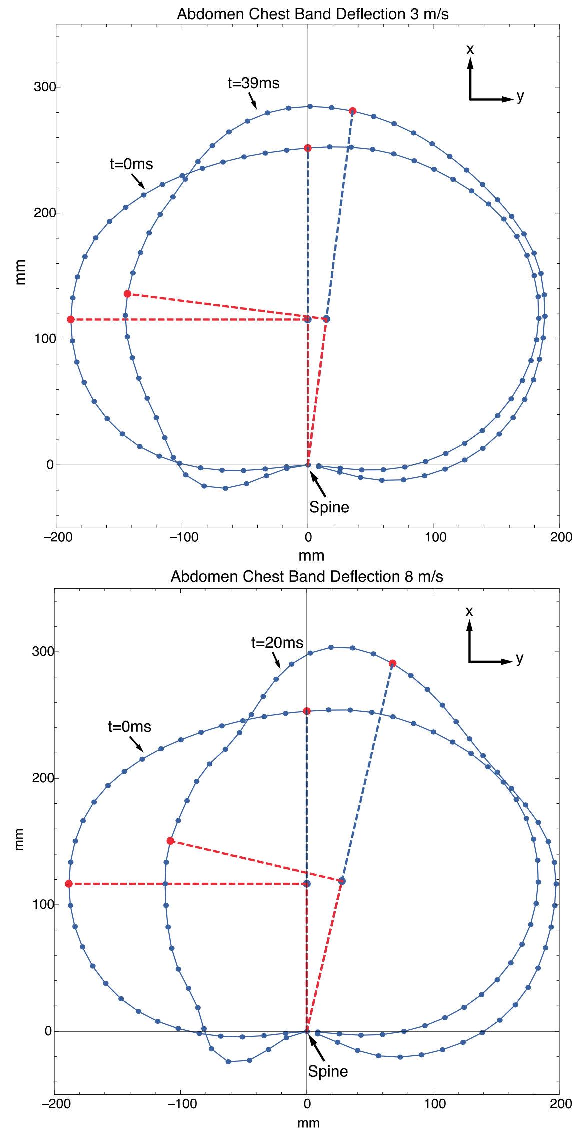

Figure 11. External WorldSID abdomen chestband contours for the 3-m/s (top) and 8-m/s (bottom) tests at the time of abdomen contact and at the time of peak abdomen deflection.

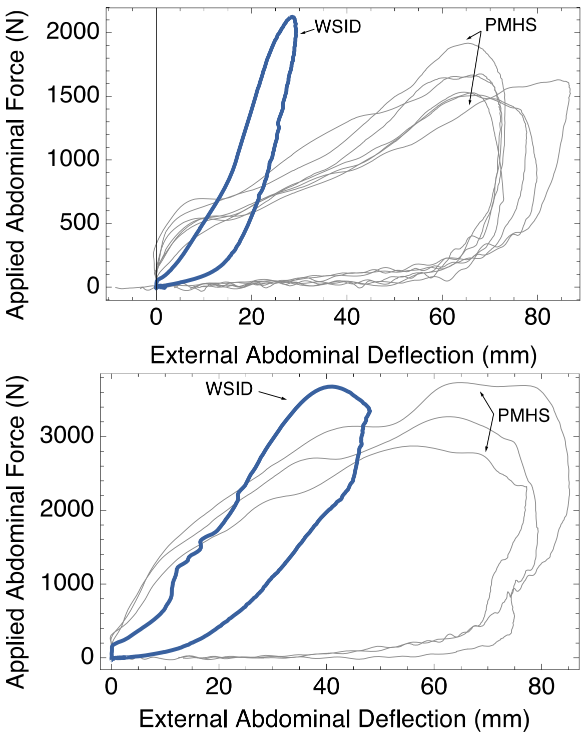

Figure 12. External abdominal force deflection curves for the 3 m/s (top) and 8 m/s (bottom) impact velocities.

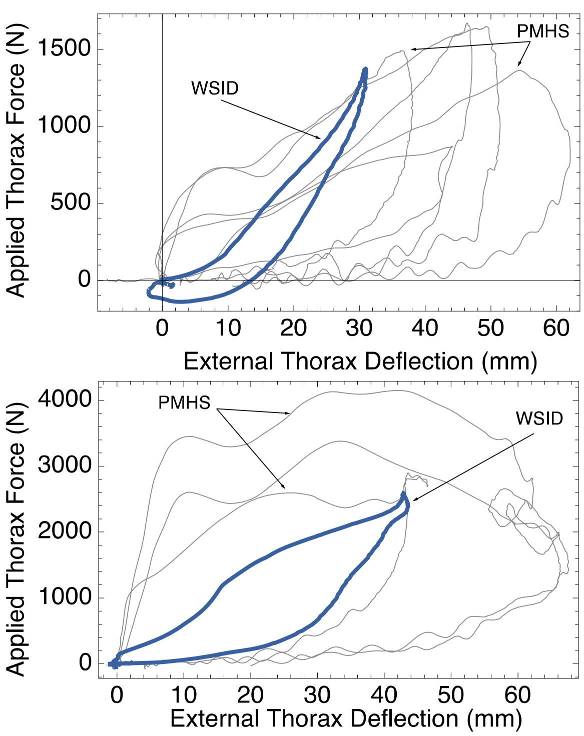

Figure 13. External thorax force deflection curves for the 3 m/s (top) and 8 m/s (bottom) condition.

DISCUSSION

In both the 3-m/s and 8-m/s tests, forces applied to the WorldSID abdomen were slightly greater than response corridors from cadavers, while peak deflection of the WorldSID abdomen was about half of the peak deflection of the cadaver abdomen. The combination of these observations indicates that the WorldSID abdomen lacks the rate sensitivity of the cadaver abdomen and therefore V*C measurements made with WorldSID may be questionable.

In the 3-m/s tests, WorldSID iliac wing and trochanteric peak forces were within, or slightly above, the cadaver response corridors, while in the 8-m/s tests, these WorldSID responses were both substantially above the cadaver response corridors. Coupled with the observation that WorldSID pelvis y-axis acceleration responses are above 3-m/s cadaver response corridors, but within the 8-m/s response corridors, this suggests that the WorldSID pelvis is too stiff and probably has too much tightly coupled mass.

The forces applied to the WorldSID thigh were higher than the forces applied to the cadaver thigh in both the 3-m/s and 8-m/s tests. This is partially because the WorldSID has more thigh flesh than most of the cadavers that were tested. As a result, the WorldSID thigh was loaded earlier in the impact than the cadaver thigh. However, the large differences between peak forces applied to the cadaver and WorldSID thighs also suggest that either the WorldSID thigh flesh is too stiff and/or the tight coupling between the femur and knee causes more mass coupling to the WorldSID thigh. This suggests the need for further research on the impact response of the thigh and leg with the lower extremities in a seated posture, particularly since ISO TR9790 doesn't provide impact response specifications for the thigh independently of the pelvis.

Peak forces applied to the WorldSID thorax in the 3-m/s and 8-m/s tests were generally within the cadaver response corridors, although the shape of the WorldSID applied thoracic force history produced in the 8-m/s test is different from the shape of the cadaver corridor. The peak external thoracic deflection of the WorldSID was also less than peak external thoracic deflections for the cadavers tested at 3 m/s and at the low end of the range of cadaver thoracic deflections produced in the 8-m/s tests. One potential explanation for this difference is that the WorldSID thoracic spine lacks the flexibility that is present in the cadaver thoracic spine and, as a result, WorldSID torso tends to tilt towards the impactor rather than deforming around it like the cadaver torso.

The magnitude of the difference between the peak external and internal deflections of the WorldSID abdomen was approximately 12-13 mm, which is similar to the thickness of the chest jacket, suggesting that the measurements of WorldSID abdomen deflection are primarily due to compression of the chest jacket. In contrast, the difference between peak internal and external WorldSID thorax deflections was approximately 20 mm, which is larger than the thickness of the chest jacket. One reason for this difference may be the chest jacket slipping relative to the ribs, such that the chestband remains more aligned with the axis of motion of the plate that loads the thorax than do the ribs. Multipoint 3D chest deflection measurements have the potential to help resolve this issue.

Some part of the response differences between the WorldSID and cadavers is due to variations in load sharing among body regions that occur from differences in external body contours. Specifically, the cadaver abdomen tends to protrude laterally more than the WorldSID abdomen, the WorldSID thorax is less tapered than the cadaver thoraces, and the WorldSID thigh flesh is slightly thicker than the cadaver thigh flesh. The former and latter of these observations likely result from the ages and sizes of the cadavers used to develop the response corridors. These cadavers were slightly heavier than the WorldSID and, as a result, had slightly wider abdomens. Cadavers were also generally older, which tends to result in lower amounts (thickness) of thigh flesh.

CONCLUSIONS

The responses of the WorldSID midsize-male thorax, abdomen, iliac wing, greater trochanter, and mid thigh were measured in a series of nearside-occupant sled-to-sled impact tests. The WorldSID was loaded with a segmented padded impactor with a 5.1-cm abdomen offset at initial velocities of 3-m/s and 8-m/s. These responses were compared to mean±1SD response corridors developed from cadaver tests conducted using similar loading conditions.

Comparisons between WorldSID and cadaver responses suggest that:

- the WorldSID abdomen is stiffer and less rate sensitive than the cadaver abdomen, and that
- the WorldSID pelvis is likely stiffer than the cadaver pelvis and has more tightly coupled mass.

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