TESTING OF THE WORLDSID-5F TO SUPPORT INJURY RISK FUNCTION DEVELOPMENT AND ASSESSMENT OF OTHER PERFORMANCE ISSUES

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ABSTRACT

Global Technical Regulation Informal Groups have directed a WorldSID Technical Evaluation Group to document the performance of the WorldSID-50M (50th percentile male) and 5F (5th percentile female).

This research contributes to the evaluation of the WorldSID-5F. It documents pendulum and sled tests carried out to aid both the biofidelity assessment by the WorldSID Informal Group and injury risk development by ISO/TC22/SC12 Working Group 6 (WG6).

Issues concerning contacts between the pelvis bone and lumbar-sacral components, and interaction between the pelvis flesh and lowest rib, were also investigated.

The WorldSID-5F test programme consisted of 26 sled and 51 pendulum tests, in a variety of impact configurations, matching the biofidelity and injury risk test requirements specified by ISO.

The WorldSID-5F generally performed as expected. The dummy biofidelity was shown to be outside of several ISO targets. However, this performance has been demonstrated previously with the Revision 1 release of the dummy and may still represent an improvement over other, currently available, side impact dummies.

Dummy handling was found to be good at typical vehicle test severities. Test-to-test use of the dummy was straightforward; however, durability is predicted to be a problem when trying to achieve the high test severities needed in the development of injury risk functions.

Contacts were detected between the pubic symphysis and anterior-inferior corner of the sacral load cell mounting and between the iliac wing and the lumbar spine mounting bracket. These contacts occurred in sled and pendulum tests at severity levels substantially below those specified for many of the biofidelity and injury risk tests.

In the pendulum test programme contacts were also detected between the shoulder and the neck bracket. Such a contact provides an uninstrumented load path.

INTRODUCTION

The WorldSID 50th percentile male crash test dummy (WorldSID-50M) was developed by a world-wide collaborative effort that was managed by the ISO WorldSID Task Force under a tri-chair representing Europe, the Americas, and Asia-Pacific. With an overall ISO biofidelity rating of 7.6 the WorldSID-50M offers a biofidelity improvement over other currently available side impact dummies such as the BioSID, ES-2, EuroSID-1 and USDOT-SID [1].

More recently, the WorldSID 5th percentile female dummy (WorldSID-5F) was developed by the European FP6 project APROSYS. The design of the 5F dummy was based on the 50M with the objective to create a family of dummies that give a consistent direction to the design of vehicle safety structures and restraint systems. Eggers *et al.* [2] reported that the WorldSID-5F has an overall ISO biofidelity rating of 7.6, equal to the 50M. Other aspects of the WorldSID-5F dummy performance, such as repeatability and reproducibility (R&R), were intended to be comparable with the WorldSID-50M performance.

The objectives of the work described in this paper were to:

- Contribute to the assessment of WorldSID-5F biofidelity by:
    - Contributing to the ISO WG6 work to scale side impact biofidelity test conditions
    - Contributing pendulum impactor and sled biofidelity tests to complement the testing carried out by other participants in the GTR WorldSID Informal Group
- Contribute to the development of injury risk functions for the WorldSID-5F by:
    - Contributing to the ISO WG6 work to define injury risk functions for the WorldSID-5F
    - Contributing pendulum impactor or sled injury risk tests to complement the testing carried out by other contributors to the GTR WorldSID Informal Group.

This paper documents the TRL test work undertaken on behalf of the European Commission with the WorldSID-5F (Build level = SBL C, Serial number SN002). It was performed whilst collaborating closely with ISO Working Groups 5 and 6 and their efforts to define the biofidelity targets and injury risk functions for use with the WorldSID-5F. The next section of the paper documents the process used by ISO WG6 and the whole body of testing that would be completed ideally with each new side impact dummy.

ISO WORKING GROUP 6 REQUIREMENTS

As mentioned, the WorldSID-5F tests performed by TRL were used in the construction of injury risk curves specific to this dummy.

The method used for the development of the WorldSID-50M dummy injury risk curves (ISO/TC22/SC12/Technical Report TR12350: 2010E [3]) was applied to the WorldSID-5F female dummy. Dummy responses and injuries from paired dummy and Post-Mortem Human Subject (PMHS) tests, performed in similar test configurations were required. However, there were not enough 5th percentile female PMHS tests available in the literature. As a consequence, the samples of PMHS used to build injury risk curves for the WorldSID-50M were considered. The PMHS test configurations considered in ISO/TC22/SC12/TR12350 are presented in the Appendix in Tables 2 and 3.

It was necessary to determine the test conditions equivalent for a 50th percentile male and a 5th percentile female to be able to pair the WorldSID-5F responses and the PMHS injuries. The anthropometry from Schneider *et al.* [4] was used to calculate the scaling factors. The test conditions were defined by the impact surface geometry and the impact speed, plus the impactor mass for impactor tests.

The geometry of the impact surface was scaled in order to load the same body region for a 50th percentile male and a 5th percentile female occupant (some examples from the scaling of the Wayne State University sled test force plates are provided in Table 1). An equivalent test condition also means that the risk of injury is the same for a 50th percentile male and 5th percentile female occupant. This was made possible by scaling both the impact speed and impactor mass. The impactor mass was scaled based on the total body mass of a 50th percentile male and 5th percentile female. Based on a mass-spring-mass model, and given the scaling of the impactor mass, the impact speed was identical for a 50th percentile male and 5th percentile female.

Using the example of a thoracic impactor test, the test condition was considered to be equivalent if the same ribs were loaded for the 50th percentile male and the 5th percentile female and if the thoracic compression (deflection as a percentage of the chest depth) was the same.

Table 1.
Wayne State University sled test force plate dimensions

WSU, along the axis of the seat pan	Allowance for mid-sized male (mm)	Dimensions for UMTRI 5th percentile (mm)
Pelvis plate length from the seat back	284	242
Centre of the knee plate relative to seatback	542	461
Knee plate width	102	87
Knee plate height	203	173

The scaled test configurations were agreed on within the ISO/TC22/SC12/WG6 group and volunteering biomechanical experts.

In some cases, the new scaled test configurations for injury risk curve development deviated slightly from those previously generated for biofidelity assessments of small female dummies. Where differences occurred, priority was given to the test set-up needed for the injury risk work, as the biofidelity of the WorldSID-5F has been assessed previously [2].

EXPERIMENTAL WORK

To help meet the testing requirements specified by ISO WGs 5 and 6, pendulum and sled tests were carried out at TRL with the WorldSID-5F dummy. The methods used and the results derived from the ensuing tests are described in the next few sections. It should be noted that some of the original PMHS tests used a linearly guided impactor. Before undertaking the test programme, it was agreed with ISO WG6 that it would be acceptable to replicate these tests with a pendulum rather than have to use a linear impactor.

Pendulum testing

As mentioned earlier, the pendulum tests to be replicated for injury risk function development are described in ISO TR12350 [3]. The tests carried out at TRL with the WorldSID-5F are described below.

INRETS shoulder tests: a series of shoulder impactor tests. In the original testing, each PMHS was seated upright, without back support. Where an upright position with the WorldSID-5F is described, the thorax tilt sensor was positioned to read 20 degrees, approximately. This is because in the upright position the spine is about 20 degrees more upright than in the standard seated position. For the PMHS tests, the impactor face was centred on the glenohumeral joint. Each subject was impacted in the pure lateral direction, 15° rearward of lateral, and 15° forward of lateral. These three impact configurations were reproduced. For the WorldSID-5F in the lateral test, the impactor alignment was 17 mm anterior (forward) and 4 mm superior (above) to the centre of the three arm mounting bolts.

The impactor speed for the oblique tests was 1.5 m/s. The pure lateral tests were conducted at the three different speeds; 1.5, 3.5 and 6 m/s.

WSU shoulder tests: another series of impactor tests to the shoulder. For the PMHS the impact face was centred on the acromion of the subject and each PMHS was impacted in the pure lateral direction. To give a similar alignment for the WorldSID-5F, the centre of the impactor was aligned 43.5 mm superior to the centre of the three arm mounting bolts. The test speed for the WSU impacts was 4.5 m/s.

ISO TR 9790 Shoulder Test 1, as described in the ISO Technical Report 9790 [5], this is based on impactor tests conducted by the APR. The axis of the impactor was aligned with the centre of the shoulder joint (the centre of the three arm mounting bolts). The impact velocity was 4.45 m/s.
The requirements for this test specify the use of a 14 kg pendulum impactor. However, because the results from this test type are also useful for injury risk function development, the dummy was tested with a 14.7 kg pendulum. It is expected that the force and deflection recorded in these tests were greater than would be the case if the test had been performed with the prescribed 14 kg impactor.

ISO TR 9790 Thorax Test 1; For ISO Thorax Test 1 tests the dummy was seated upright with its arm raised so that the side of its thorax was clear to

be impacted. The face of the impactor was centred on the lateral aspect of the thoracic rib structure and the dummy's thorax was impacted laterally at velocities of 0.9, 4.3 and 6.1 m/s.
Regarding the vertical alignment, additional tests were carried out to investigate whether differences could be noticed between two subtly different alignments. The two options were:

1. Align the centre of the impactor with the middle of the 2nd thoracic rib
2. Align the lower border of the impactor with the lower border of the 3rd thoracic rib (position about 5 mm higher than Option 1)

In either case the arm did not interfere with the thoracic loading.

As noted in the previous section on the shoulder test, these thorax requirements specify the use of a 14 kg pendulum impactor. However, because the results from this test type are also useful for injury risk function development, the dummy was tested with a 14.7 kg pendulum. Again, it is expected that the force and deflection recorded in these tests were greater than would be the case if the test had been performed with the prescribed 14 kg impactor.

WSU/GM thorax tests use a setup very similar to that used for the ISO (HSRI-based) tests. The key difference between these and the other thorax tests, was the requirement to conduct these obliquely, 30 degrees forward of lateral. This was achieved by sitting the dummy on the bench normally, then rotating the bench through 30 degrees relative to the line of the pendulum action (so as to rotate the dummy about its z-axis). The alignment then translated around the thorax so as to still be centred horizontally to strike the most lateral aspect of the thorax. The vertical alignment was the same as the previous tests, taking the approach of picking the level which would be centred with the middle of the middle thoracic rib, if it had been struck laterally.

The impact speed for this test configuration was 6 m/s. Additionally, the original tests also indicate that a test at 8.7 m/s should be carried out. This higher test speed was not possible within the facility at TRL and without the likelihood of causing damage to the dummy and its instrumentation. Therefore, alternative tests were performed at tests speeds of 2, 3, 4, 5, 5.5 and 6 m/s to support the scaling up of results to predict output at 8.7 m/s.

The peak y-displacement against test speed is shown in Figure 1. The results show that there is a reasonable linear correlation between test speed and rib displacement and therefore it should be possible to use this method for extrapolation to higher test speeds.

UMTRI thorax tests: In the original series, each PMHS was suspended in a seated position, either with the arms positioned above the shoulder and the hands above the head or with the arms down. The metal impact face had various materials affixed to it to produce different force-time histories and load distributions. However, only the bare-faced impactor tests were reproduced with the WorldSID-5F. The test speed was 2 m/s with a pure lateral impact direction.

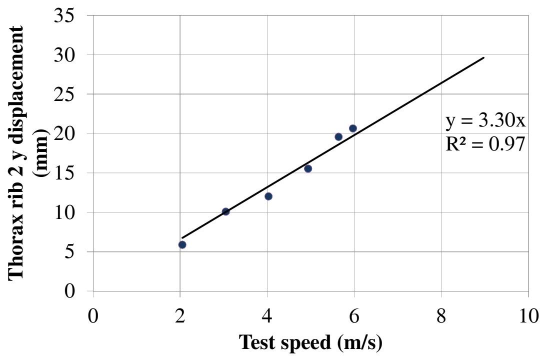

Figure 1. Peak y-axis displacement against test speed for WSU/GM thorax pendulum tests.

WSU/GM pelvis tests: Each PMHS was suspended in a standing position, with the arms positioned above the shoulder and the hands above the head. For the pelvis impacts, the impact face was centred on the greater trochanter. For the WorldSID 5th this was reproduced with the impactor aligned 9 mm forward and 29 mm inferior (downwards) to the H-point.

This test series required a test at 10m/s, however this speed could not be reached by the TRL pendulum. Therefore a series of tests were performed at lower speeds to investigate whether the data could be extrapolated to higher speeds.

The tests speeds chosen were 3, 4, 5, 6 and 7 m/s. Figure 2 shows the lateral acceleration and pubic force against test speed.

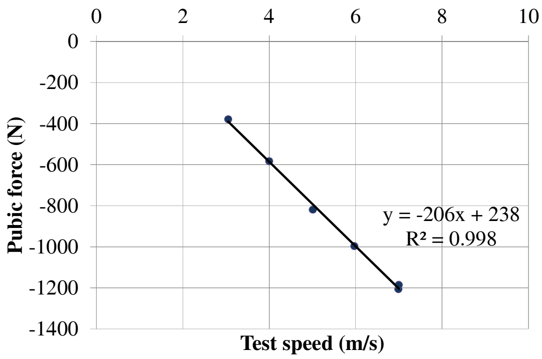

Figure 2. Pubic force against test speed for WSU/GM pelvis tests.

The results show that there is a linear correlation, however this would not pass through the origin, and therefore at test speeds lower than 3m/s the extrapolation may not be accurate enough. Similar results were obtained for the lateral acceleration, lateral iliac force and x-axis iliac moment.

Sled testing

Currently, there are three sled test conditions selected by ISO for use in the biofidelity assessment of, and injury risk function development for, side impact dummies. These conditions are taken from test series conducted with PMHS which have been reported in the literature. The three conditions can be described by the laboratory at which the work was undertaken, and are:

- Heidelberg (University of…)
- WSU (Wayne State University)
- MCW (Medical College of Wisconsin)

The sled bench design used in this project is capable of replicating the set-up conditions of all three test types.

Heidelberg: The oldest of the three test conditions is that reported by Marcus *et al.* [6]. It was intended to recreate the rigid wall tests at both 24 km/h (6.7 m/s) and 32 km/h (8.9 m/s).

Wayne State University: According to Cavanaugh *et al.* [7], the subjects from the WSU tests were positioned on a Heidelberg-type seat fixture. The seat was mounted to a sled and accelerated up to velocities of 6.6 to 10.5 m/s.

The subset of the original WSU tests recreated at TRL with the WorldSID-5F was the rigid wall tests, specified by ISO to have speeds of either 6.3 or 8.9 m/s. As in the original tests, the subject sat against a two-bar seat back. For those tests, the hands were placed in the lap of the subject. To replicate the position of the upper arms the WorldSID-5F half-arms were positioned slightly anteriorly to the mid-axillary line so that they did not bridge over the thorax ribs.

Medical College, Wisconsin: The Medical College of Wisconsin (MCW) and the NHTSA Vehicle Research and Test Centre (VRTC) performed a suite of side impact tests. According to Maltese *et al.* [8], they were conducted at two different speeds (6.7 and 8.9 m/s), with and without impact surface padding, and using a variety of impact wall geometries. At TRL only the rigid wall tests were reproduced, as the padding material was not readily available.

The sled apparatus was of the Heidelberg design. Test subjects were seated on the bench of the impact sled approximately one metre from the load wall. Just after the sled achieved the prescribed velocity change, the occupant contacted the load wall. The TRL recreation of the MCW conditions incorporated the load wall on the sled.

The load wall for the MCW tests was divided into four sections, one each to contact the thorax, abdomen, pelvis and legs. The change in sled velocity was either 6.7 or 8.9 (± 0.3) m/s. Load plates were either fixed in the same plane, or the thoracic or pelvic plate was offset, one at a time per test, toward the occupant. In flat wall and pelvic offset tests, the WorldSID-5F was seated with arms down, such that the arm was interposed between the thorax and load wall. In thoracic and abdominal offset tests, arms were raised to expose the thorax and abdomen directly to impact from the load wall. This was to match the PMHS positions in the offset wall tests, with the hands positioned up on the opposite shoulder.

RESULTS

As described in the introduction, one of the purposes for conducting these tests was to pass the results to ISO WG6 for use in the development of injury risk functions for the WorldSID-5F. The data from these tests have been made available to that group for that purpose. The tables of peak values are too large to be shown in this paper. However, they are available in the project report prepared for the European Commission [9].

Pendulum test results

Further to the production of test results for use in the development of injury risk functions, other interesting results from the pendulum testing are described in the following sections.

Shoulder biofidelity: the ISO (APR) shoulder test is used to assess shoulder biofidelity, according to ISO TR 9790.

The requirement for peak shoulder deflection is that the resulting value lies between 28 and 33 mm. The filtered shoulder deflections from two tests with the WorldSID-5F gave a mean peak value of 31.1 mm. This is within the required range. However, when the responses are normalised according to the ISO description, the mean peak value drops to 25.8 mm; below the lower boundary of the requirement.

The pendulum force response also suffers through the normalisation process with the filtered responses prior to normalisation lying closer to the required corridor than the normalised curves. These pendulum force results from the same two shoulder tests are shown in Figure 3.

Due to a conflict between the biofidelity and injury risk test specification, these tests were performed with a pendulum that was five percent heavier than that specified for the biofidelity evaluation. The force and deflection would be expected to be lower if conducted with the correct mass of impactor. This would help to bring the pendulum force response and the normalised shoulder deflection peak values closer to the corridor. However, the magnitude of the change is unlikely to bring the normalised results within the corridor.

On the basis of these results it seems as though the shoulder of the dummy is slightly too stiff.

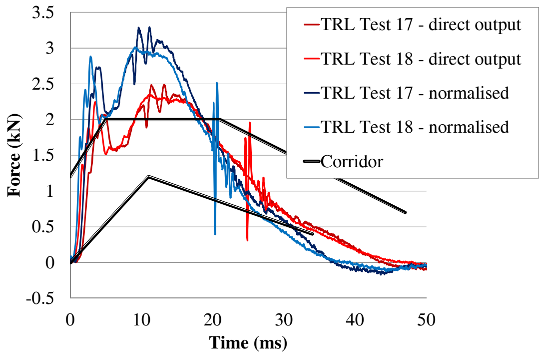

Figure 3. Shoulder test pendulum force response at 4.5 m/s.

Thorax biofidelity: As thorax pendulum tests were carried out using the ISO TR 9790 Thorax Test 1 set-up it is possible to comment on the thorax biofidelity of the WorldSID-5F in these tests. The biofidelity requirements from these tests concern the impactor force and the upper thoracic spine acceleration. Typically, an accelerometer at the T1 position is used to give the thoracic spine acceleration. However, with this WorldSID-5F only the T4 position was available for analysis. Therefore, Figure 4 shows the impactor force response from these tests compared with the requirement and Figure 5 shows the T4 lateral acceleration plotted against the upper thoracic spine acceleration corridor.

As described earlier, two different alignments of the impactor were tried with this test set-up. Firstly the middle of the impactor was aligned with the middle of the mid-thoracic rib and alternatively, the lower edge of the impactor was aligned with the lower edge of the third thoracic rib. Results from these two variations in set-up are shown in the following two figures.

When considering the force it is clear that the dummy does not meet this requirement. The duration of the response is too short for the corridor and depending on whether the response is normalised or not the peak force is either just inside the upper corridor limit or too high, respectively.

The influence of the impactor alignment is a reduction in peak force with the bottom edge of the impactor aligned with the lower edge of the third thoracic rib. The extent of this effect with the WorldSID-5F is sufficient to bring the impactor peak force within the limits of the biofidelity corridor.

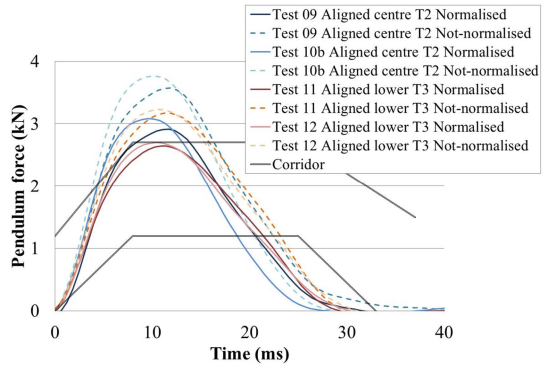

Figure 4. Thorax pendulum test impactor force response.

When considering the spinal accelerations then again the duration of the dummy response is too short. Also the peak acceleration, either normalised or not, is above the upper corridor limit. With the thoracic acceleration there seems to be less influence from the impactor alignment than was the case with the pendulum forces.

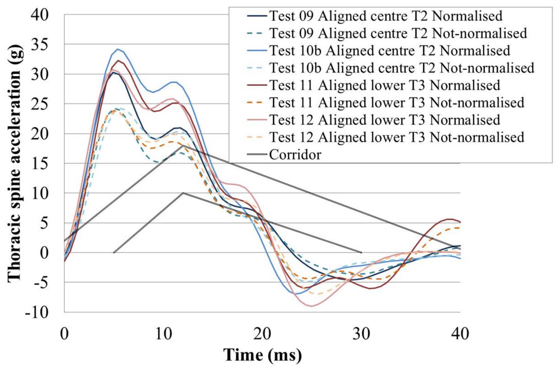

Figure 5. Thorax pendulum test upper thoracic spine acceleration.

These thorax biofidelity tests were carried out with a 14.7 kg pendulum rather than the 14 kg impactor specified in the requirements. The effect of testing with a heavier pendulum would be expected to give higher peak forces and accelerations than testing with a lighter impactor. This may help bring the pendulum force responses closer to the corridor. However, the 0.7 kg difference in this test set-up would be unlikely to account for the deviation in spine acceleration response from the required corridor.

Sled test results

It was expected that sled tests at 6.7 or 8.9 m/s would be conducted. However, due to concerns over the dummy's robustness under these conditions and the ability to provide meaningful measurements without damaging the instrumentation (i.e. reaching mechanical limits of measurement with the 2D IR-TRACCs), no tests were carried out above 6.3 m/s. To provide data for impacts above 6.3 m/s extrapolation has been used, where possible.

For the shoulder deflection it appeared that a mechanical limit of about 41 mm of deflection was reached in the Wayne State University (WSU) test at 6.3 m/s.

The consequence of reaching a mechanical limit is that whilst the impact speed shoulder deflection relationship may be linear up to this point, a plateau would be expected in deflection values at higher speeds. This is shown in Figure 6 where a linear line of best fit can be imagined for test speeds between 0 and 6 m/s. Above this speed the mechanical limit, as demonstrated at 6.3 m/s, would be expected to prevent further increases in shoulder deflection values. However, it is still possible to extrapolate beyond the point even though in practice the dummy cannot measure further deflection. This extrapolation can be considered as the best estimate of what would happen if the shoulder contact preventing further deflection was avoided. It is with this idea in mind, and using the linear relationship of the best fit trendline, that extrapolated shoulder deflection values for the higher severity WSU tests were derived.

When looking for potential sources of the mechanical contact preventing more than about 40 mm of shoulder deflection it became clear that contact could occur between the shoulder load cell and the lower edge of the neck bracket (Figure 7).

The bottom of the neck bracket in the WorldSID-5F increases in width from the top of the spine box upwards. This means that when there is no vertical displacement of the shoulder rib, it could be compressed until the shoulder load cell went all the way to the spine box. However, the more vertical displacement there is of the rib, the less y-axis deformation is possible. The extreme situation is that which occurred in the WSU tests where only 40 mm of lateral deformation is possible. In this case the shoulder load cell seems to have contacted the widest part of the neck bracket.

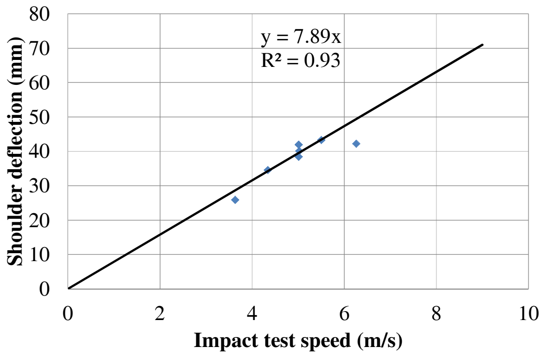

Figure 6. Peak shoulder deflection values from WSU sled tests at various impact speeds.

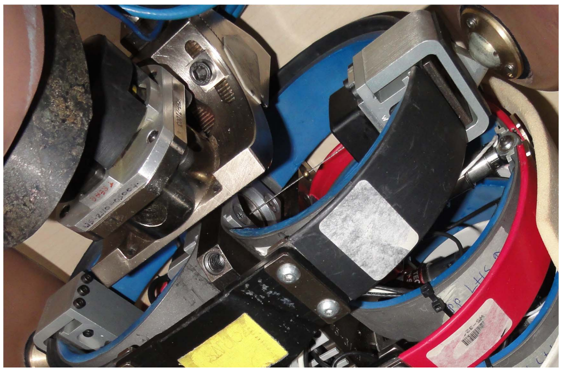

Figure 7. Neck and upper thorax of WorldSID-5F.

In the Heidelberg tests, higher shoulder deflection values were recorded than in the WSU tests. It may be that differences in the force plate configurations between the WSU and Heidelberg setups allow the hard limit for shoulder deflection to be avoided during the Heidelberg tests. It is assumed that some feature of the Heidelberg tests produces less vertical displacement of the shoulder rib than was the case in the WSU tests. Hence more lateral displacement is possible before a hard contact is made with the neck bracket.

With the variety of impact speeds for the rigid, flat wall Medical College of Wisconsin (MCW) tests similar extrapolation can be set-up as for the WSU tests. A similar approach has also been used for the other configurations. However, it should be noted that not all conditions were tested at more than one impact speed. This means that the extrapolation is reliant on one real data point and forcing the line of regression to go through the origin. This is not a robust method for determining expected values at higher severities.

With the y-axis rib deflection measurements, the line of best fit through the peak values from the sled tests supported a negative deflection intercept value at 0 m/s. Assuming that the physical meaning of this negative intercept is not plausible, this suggests that at low speeds the relationship between peak value and impact speed changes from that observed for the range of speeds tested. This serves to illustrate the danger of assuming constant behavioural relationships beyond the spread of test conditions evaluated. In terms of the test results, this behaviour means extrapolated values cannot be provided for test conditions without more than one impact speed.

The relationship between impact speed and x-axis Viscous Criterion (V*C) did not give a high r^2 correlation coefficient (0.42). Hence, extrapolation from these data was not appropriate. However, the MCW tests provided a much higher correlation value, $r^2 = 0.93$, though again the intercept was negative. In contrast, the left (struck) side sacro-iliac moment about the x-axis from the MCW flat wall tests did not provide a high correlation with impact speed ($r^2 = 0.05$), whereas the WSU tests provided a good correlation for this measure ($r^2 = 0.96$).

<u>Thorax biofidelity:</u> Heidelberg testing is used within ISO TR 9790 to assess both thorax and pelvis biofidelity. A 6.8 m/s test is required for Thorax Test 5. In the sled test programme carried out at TRL, impacts above 6.3 m/s were not carried out because of concerns over dummy breakages. Instead, 5 m/s was used as a reference speed which could be performed safely (without substantial risk of dummy breakages) with each of the three setups.

Heidelberg tests were only performed at 5 m/s. With regard to biofidelity, it is expected that the test at 5 m/s can provide some useful information. The thorax plate force response, with and without normalisation, is shown in Figure 8.

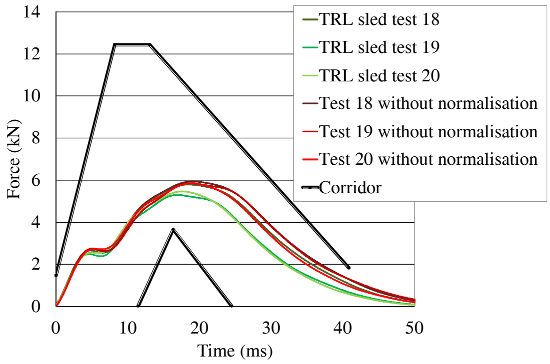

Figure 8. Heidelberg thorax plate response (5 m/s rigid plate tests, corridor for 6.8 m/s response).

It is clear from Figure 8 that at the reduced impact speed of 5 m/s, the WorldSID-5F meets the thorax plate force response corridor. It is expected that the response at the correct biofidelity test speed of 6.8 m/s could also remain within the corridor limits. However, it would be much closer to the upper corridor boundary.

Within the thorax biofidelity assessment there are also specifications for the subject accelerations. Accelerations are intended to be matched with requirements for the upper and lower spine. With the WorldSID-5F, accelerations from T4 and T12 have been used for this purpose. There is also a target for the peak lateral acceleration from the impacted rib. In this case the peak lateral acceleration values from Thorax ribs two and three are reported. A 100 Hz Finite Impulse Response filter was used to process the dummy acceleration signals prior to the peak value being taken. They have also been normalised using the ratio derived from the effective and standard mass estimates (R_a = 1.02 to 1.11).

The acceleration results showed that the peak spine acceleration is too low for the ISO target boundaries; whereas, the rib acceleration is just on the limit, though only if the higher acceleration value from Thorax rib 3 is dismissed. Again, it should be remembered that this test was conducted at 5 m/s and not the 6.8 m/s expected for use with these requirements. It should be expected that the acceleration values would increase when tested at a higher speed. This would move the spine accelerations closer to the targets whilst probably not achieving the required shift to produce values within the limits. Any increase in the rib acceleration would take it beyond the upper boundary limit. In essence it seems as though the rib acceleration is too high, whereas the spine acceleration of the WorldSID-5F is too low. This behaviour may be a consequence of the large spine box in the small female WorldSID which, apparently, had to be kept at the same size as the spine box in the 50th percentile dummy to house the data acquisition modules. The consequence of this is that proportionally more mass is located in the spine of the WorldSID-5F than in the larger 50M or would be expected in a human.

<u>Abdomen biofidelity:</u> The only abdomen biofidelity requirements set for the tests carried out at TRL were for the Wayne State University sled tests. Requirements are available for both 6.8 and 8.9 m/s rigid wall tests. However, the WorldSID-5F was only tested at speeds up to 6.3 m/s.

To give some indication of how the dummy response scales with impact speed a variety of test speeds up to the peak of 6.3 m/s were used. The abdomen results from these tests are plotted against the 6.8 m/s corridor in Figure 9.

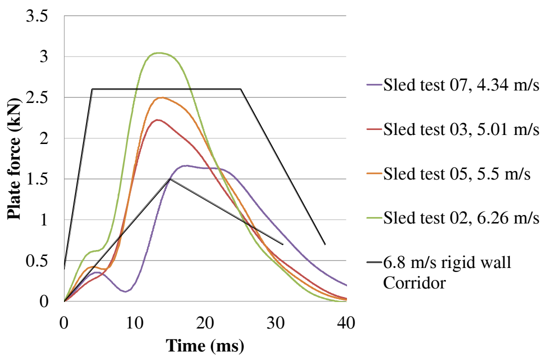

Figure 9. Wayne State University abdomen plate response (6.8 m/s rigid plate test requirement).

The force measured at the abdomen load plate increases with increasing impact speed. When tested at 6.3 m/s it had already exceeded the upper boundary of the biofidelity corridor. This indicates that the abdomen of the dummy is too stiff for the required response.

Pelvis biofidelity: The Heidelberg sled tests are also used in the evaluation of the pelvis biofidelity of side impact test dummies. Again, it must be noted that the target impact speed for the flat, rigid wall Heidelberg tests is either 6.8 or 8.9 m/s. As such, the test severity used to produce these results is substantially lower than expected for comparison with the biofidelity requirements. For this reason only the 6.8 m/s requirements are considered here.

From these results the pelvis acceleration is slightly too low when tested at a lower severity. This would improve as the impact speed is increased towards the necessary level. However, the pelvis plate force is already above the upper limit. This will move further from the requirements at a higher severity.

It was noted that at 5 m/s there was contact between the lower pelvis iliac wing and the sacro-iliac load cell and cable cover. However, there was no contact recorded between the upper central pelvis iliac wing and the lumbar spine mounting plate. The positions of the contact switches used to determine this are described later.

For the Wayne State University (WSU) tests, pelvis response requirements are also given for both 6.8 m/s and 8.9 m/s rigid wall impacts. As tests with the WorldSID-5F were not carried out above 6.3 m/s only the lower severity requirements are considered.

The peak lateral pelvis acceleration result is within the boundaries of the desired response. It is also likely that this could still be met even when the impact speed is increased by nine per cent.

The other part of the WSU pelvis biofidelity requirement concerns the pelvis plate force. The dummy responses from the range of impact speeds tested are shown against the biofidelity corridor in Figure 10. Unfortunately, for the test at 3.63 m/s the dummy had leaned substantially towards the impact wall by the time it made contact; hence the pelvis response is quite different to the other tests.

It can be seen that when an impact speed of 6.3 m/s is reached, the pelvis response has a peak already above the upper limit of the corridor. In agreement with the Heidelberg pelvis evaluation this suggests that the WorldSID-5F behaviour transfers more force through the pelvis than is expected based on the biofidelity requirements.

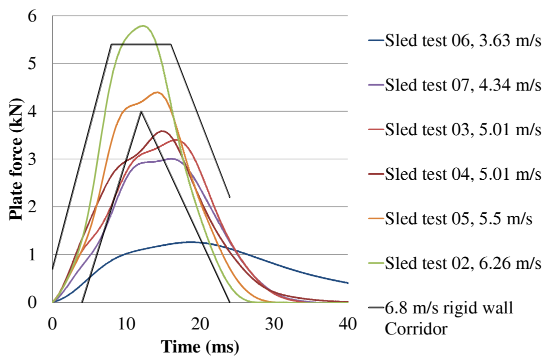

Figure 10. Wayne State University pelvis plate response (6.8 m/s rigid plate test requirement).

Pelvis interaction

Concerns had been raised in the WorldSID-5F Technical Evaluation Group over a non-instrumented load path in the pelvis. Contact reportedly occurred between the pelvis bone and the metal pelvis insert (which provides the mounting for the pelvis instrumentation and spine attachment). To detect contact, and the duration of that contact, a solution has been demonstrated where self-adhesive conductive foil is wrapped around the appropriate part of the pelvic bone to make a contact switch with the pelvis insert. A similar approach was taken at TRL to detect such a contact, in the following areas:

- The lower pelvis iliac wing with the sacro-iliac load cell and lumbar load cell cable cover
- The upper central pelvis iliac wing with the lumbar spine mounting plate

These areas and the corresponding area of the lumbar and sacro-iliac structure were fitted with the contact switches.

To provide input for possible future redesigns of the dummy pelvis components, a series of pendulum tests to impact the pelvis was used to evaluate the severity of test at which the contact occurs. The dummy was seated on a metal bench and impacted with a 14.7 kg 145 mm circular faced pendulum. The test speed was increased in increments of 1 m/s from 3 m/s to 7 m/s.

Humanetics provided modified parts with smaller volumes in critical areas to evaluate whether this improved the situation. The modified parts were fitted to the dummy and the testing series was repeated. The results from the contact switches are shown in Table 1.

Table 1.

Results of testing with original and modified pelvis-iliac and lumbar spine components

	Original parts			
Test speed (m/s)	Upper contact	Duration (ms)	Lower contact	Duration (ms)
3	No	-	-	-
4	No	-	Yes	8
5	Yes	7	Yes	10
6	Yes	10	Yes	13
7	Yes	10	Yes	14

	Modified parts			
Test speed (m/s)	Upper contact	Duration (ms)	Lower contact	Duration (ms)
3	No	-	No	-
4	No	-	No	-
5	No	-	Yes	5
6	Yes	3	Yes	2
7	-	-	-	-

The results show that there is contact at the lower part of the pelvis bone with the sacro-iliac load cell from 4 m/s and upwards. There is contact with the upper part of the pelvis bone and lumbar spine mounting plate from 5 m/s and upwards. These results were improved with the modified parts to 5 m/s and 6 m/s respectively.

Pelvis-rib interaction

In previous tests with the WorldSID-50M it had been noted that it may be possible to accidently seat the dummy with either:

- The lower abdomen rib on the flat upper face of the anterior pelvis flesh
- The anterior pelvis flesh pushed behind or "tucked under" the lower abdomen rib

In order to investigate the effect of this and a possible solution to the problem, additional tests were performed with the WorldSID-5F dummy. The tests performed were sled tests at 5 m/s with just the MCW abdomen plate and load cells on the impact face. Each test was repeated.

To push the anterior pelvis flesh under the lower abdomen rib, the dummy had to be leaned forward on the seat, the pelvis flesh tucked under the rib, and then the dummy leaned back into position. The dummy pelvis when tucked under the lowest ribs and the sternum is shown in Figure 11. The required steps to obtain this position were considered to be relatively extreme in the context of usual dummy positioning in a vehicle seat.

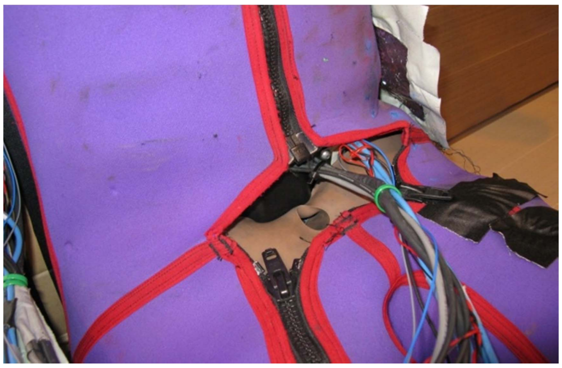

Figure 11. Dummy setup with pelvis-rib interaction.

The lower abdomen rib rotation and change in length in IR-TRACC are shown in Figures 12 and 13. In the test with forced pelvis-rib interaction (with the pelvis flesh deliberately pushed under the abdominal rib) there is less rotation, but greater change in IR-TRACC length than in the standard test.

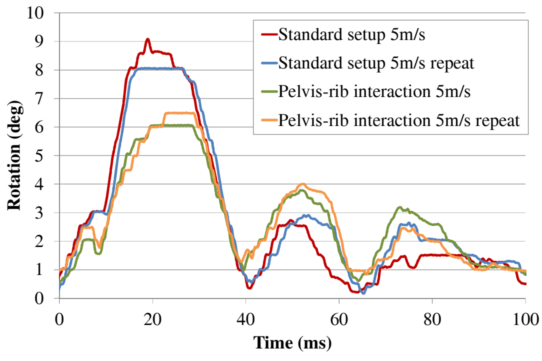

Figure 12. Lower abdomen IR-TRACC rotation for standard dummy setup and setup with pelvis-rib interaction.

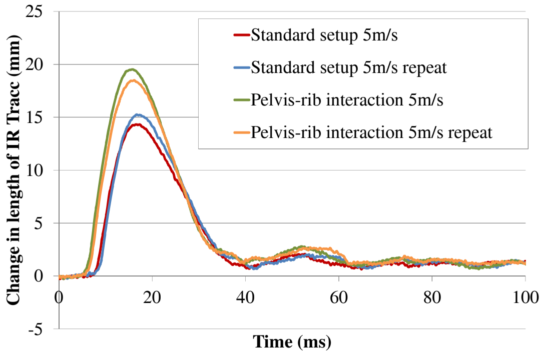

Figure 13. Change in length of lower abdomen IR-TRACC for standard dummy setup and setup with pelvis-rib interaction.

In order to reduce the possibility of accidently seating the dummy with the pelvis flesh interacting with the lower abdomen rib, modifications were made by TRL to the anterior pelvis flesh. Parts of the flesh were cut away to reduce the volume of the flesh in this region. The profile of the anterior surface was not affected by the removal of the foam behind it, although the stiffness of this part of the pelvis flesh would be reduced. Figures 14 and 15 show the flesh before and after the modification.

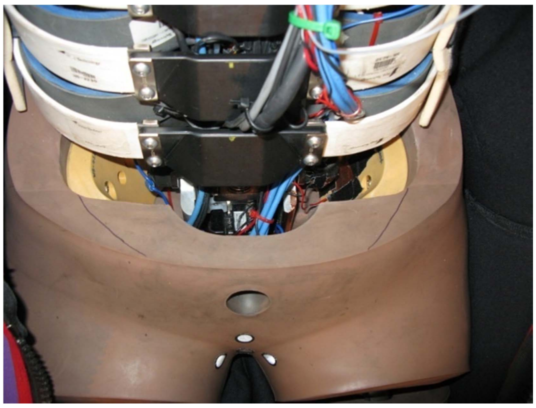

Figure 14. Anterior pelvis flesh before modification.

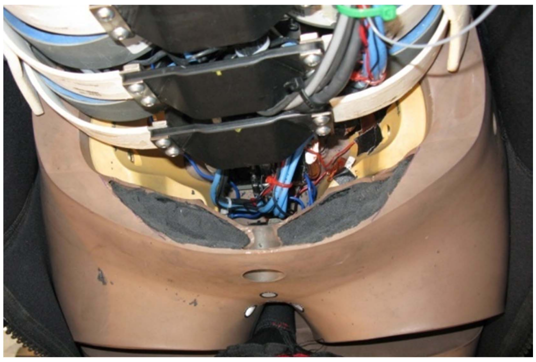

Figure 15. Anterior pelvis flesh after modification.

After making the modifications to the pelvis flesh the dummy was re-tested. With the modified flesh, the lower abdomen rib rotation and change in length of the IR-TRACC were greater than with the standard dummy, there was also a greater resultant displacement. This indicates the standard dummy pelvis constrains the motion of the lower abdominal rib in this sled test condition. If it is possible for the rib to become caught up on top of the flesh, as in the simulated pelvis-rib interaction tests, then the motion is further constrained and there can be an increase in the plate force measured by the load cell wall.

DISCUSSION

Results from this test work have already been presented to the WorldSID Informal Group (IG). Test data have also been offered to ISO WG6.

Based on the discussions held within the Informal Group, the manufacturer of the WorldSID-5F has proposed to revise the shoulder and pelvis of the dummy. Depending on the exact modifications an opportunity may come about to evaluate experimentally the dummy at higher severities. Therefore more of the severe injury risk tests could be performed perhaps leading to the development of improved risk functions.

All tests were made with one WorldSID-5F dummy, so there has been no evaluation of the dummy reproducibility in this work. It is hoped that these results will be compared with results from other dummies. Until that point there remains the risk that the dummy used by TRL is not representative of other WorldSID-5Fs.

Handling

As a result of the robustness issues and wanting to investigate the benefit of new pelvis designs, much time was spent working on the dummy and assembly/disassembly. Based on these experiences it has become clear that some comments are warranted regarding the ease of using the WorldSID-5F.

1. The pelvis was disassembled and reassembled four times during the testing programme. This is an extremely time-consuming task. There appears to be no easy way of sliding the pelvic bone back into the pelvis flesh. As a result it is very easy to put a lot of strain onto the cables running between the upper body of the dummy and the pelvis. Consideration should be given to making this task easier for the sake of protecting instrumentation and easing the process for the technician.
2. It is not clear why the cabling running from the data acquisition modules in the upper body of the dummy to the pelvis and legs cannot be split where the dummy is split. This seems as though it would be an extremely useful design feature to mitigate the risk of instrumentation damage when working on the dummy, whilst being separated top to bottom. At the very least sufficient cable lengths should be supplied to allow a reasonable distance between the two dummy portions.
3. It is very difficult to attach the bolts that hold the femoral heads into the acetabula of the pelvic bone with the full complement of instrumentation in the dummy pelvis.

CONCLUSIONS

A large programme of side impact sled and impactor tests has been conducted. The data will be used in the assessment of the WorldSID-5F biofidelity and also in specifying injury risk functions to be used with this dummy.

The dummy was used in 26 sled tests and 51 pendulum impacts. Throughout this test programme the dummy functioned well.

- The dummy biofidelity was shown to be outside of the ISO requirements in a number of areas. However, this performance has been demonstrated previously with the Revision 1 release of the dummy and may still represent a 'good' rating compared with other side impact dummies.
- Test-to-test use of the dummy is straight forward and no significant issues occurred with the data acquisition system, etc.

Durability is a problem when trying to achieve test severities needed for the development of injury risk functions.

- Sled tests were limited to impact speeds less than required for the higher severity biofidelity tests
- Whilst the highest severity injury risk tests may be outside the range of normal reasonable use of the dummy, there is still the need to provide dummy measurements in equivalent tests in order to generate robust injury risk functions
- Without dummy measurements from high severity tests it may be difficult to generate robust injury risk functions for this dummy

Dummy design changes which seem to be necessary to be able to perform these tests are:

- Improved displacement and angle range of motion for the 2D IR-TRACCs
- Removal of the contact potential between the shoulder load cell and the neck bracket
- Greater space for iliac wing bending without contact occurring with the sacro-iliac load cell or lumbar spine mounting in the pelvis

Results from this test work have already been presented to the WorldSID Informal Group (IG). Humanetics has already proposed to revise the dummy. The revisions will be based on this test work and similar findings from other groups participating in the TEG.

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APPENDIX – ISO TEST SERIES

Table 2.

Original Test Series Of PMHS Impactor Tests

Test Series	Direction	Impact surface	Impactor face geometry	Range of impact speed (m/s)
Shoulder impactor tests				
APR [10]	Lateral	Rigid	circular	4.2-4.6
INRETS [11]	Lateral, forward and rearward from lateral	Rigid	rectangular	1.3-6.1
OSU series 1 [12]	Lateral	Padded	rectangular	3.7-6.8
OSU series 2 [13]	Lateral and forward from lateral	Padded	rectangular	4-7.6
WSU [14]	Lateral	Rigid	circular	4.3-7.0
Thoracic impactor tests				
HSRI [15]	Lateral	Rigid	circular	0.9-6.1
WSU [16]	Forward from lateral	Rigid	circular	6.0-8.7
OSU [17]	Lateral and forward from lateral	Rigid	circular	2.5
UMTRI [18]	Lateral and forward from lateral	Rigid or padded	circular	1.9-8.5
Abdomen impactor tests				
WSU [16]	Forward from lateral	Rigid	circular	9.8
OSU [19]	Lateral	Padded	rectangular	6.0-12.3
Pelvis impactor tests				
WSU [16]	Lateral	Rigid	circular	4.0-10.3
ONSER [20]	Lateral	Rigid	circular	5.8-14.0
UMTRI [21]	Lateral	Rigid or padded	circular	5.1-26
INRETS [22]	Lateral	Rigid	rectangular	3.2-13.7

Table 3.

Original Test Series Of PMHS Sled Tests

Test Series	Description of Sled Tests
Heidelberg [6]	8.2 m/s impacts into a flat impact surface with separate instrumented plates for the thorax and pelvis. The impact surface was rigid.
WSU [23], [24]	6.7 to 8.9 m/s impacts into rigid or padded plates for the shoulder, thorax, abdomen, pelvis and knee.
MCW & OSU [25]	6.7 to 8.9 m/s impacts into rigid or padded plates for the thorax, abdomen, pelvis and lower extremity. The plates were either flat, one plate offset by 110-mm, or the thorax and abdomen plates were angled.