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Abdomen Impact Testing of the Hybrid III Rail Safety (H3-RS) Anthropomorphic Test Device

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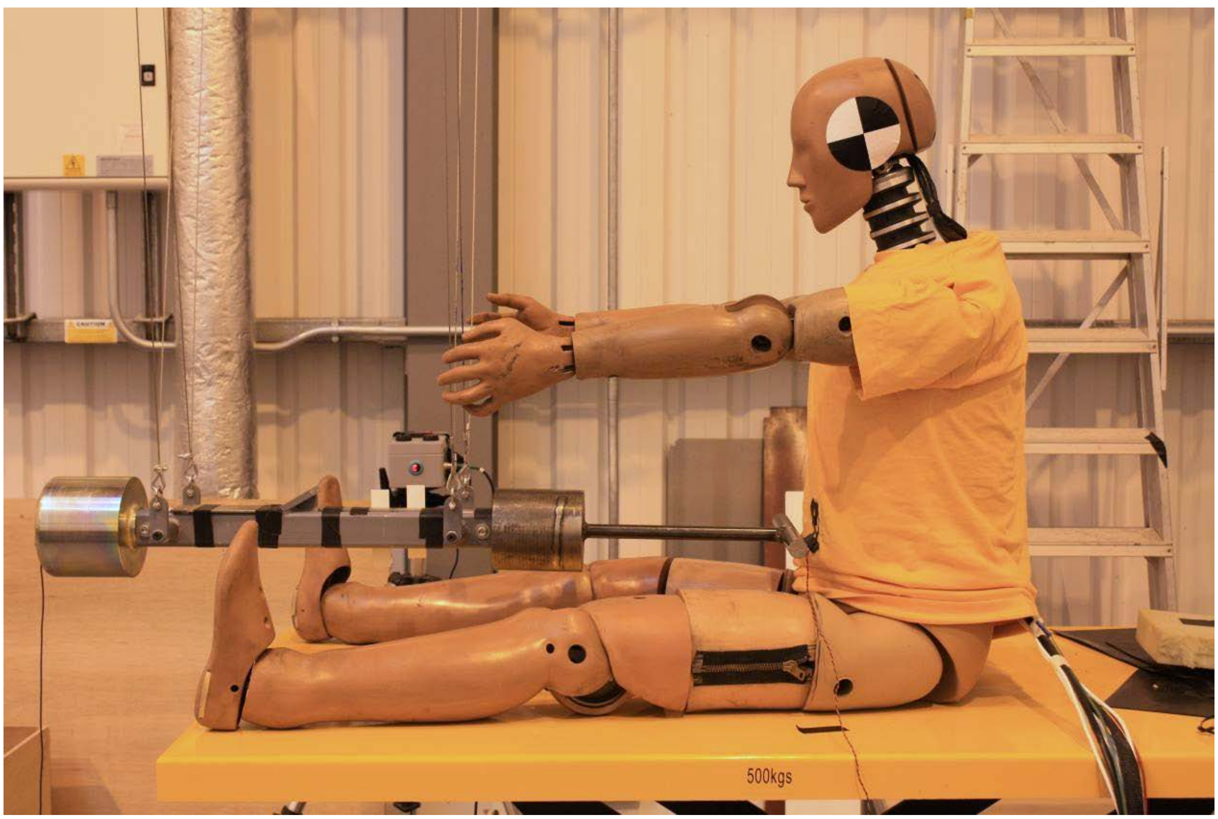

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13. ABSTRACT (Maximum 200 words)
The Hybrid III Rail Safety (H3-RS) anthropomorphic test device (ATD) is a crash test dummy that was developed in the UK to evaluate abdomen and lower thorax injuries that occur when passengers impact workstation tables during train accidents. The H3-RS is similar to the standard Hybrid III 50th percentile male ATD used in car crash test regulations worldwide, but with a more humanlike abdomen response under table-edge loading conditions and with additional instrumentation to evaluate injury risk at multiple bilateral locations. The objectives of this study were to evaluate the accuracy of the current H3-RS abdomen deflection transducers, to evaluate the biofidelity of three abdomen bag designs, to evaluate test repeatability, and to evaluate sensitivity to variations in impact location, and impactor geometry, mass, and velocity. The ATD was tested using an eight-wire pendulum impactor with various impactor faces and masses defined in biofidelity requirements and developed specifically for this study. The biofidelity of the H3-RS was good. Repeatability and sensitivity were appropriate. Recommendations resulting from this study include investigating further the performance of the lower abdomen deflection transducers and, if necessary, specifying a more robust alternative transducer.

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1 foot (ft)	=	30 centimeters (cm)
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1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

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1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
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10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

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1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
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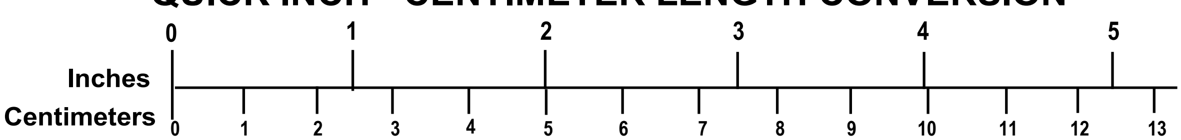

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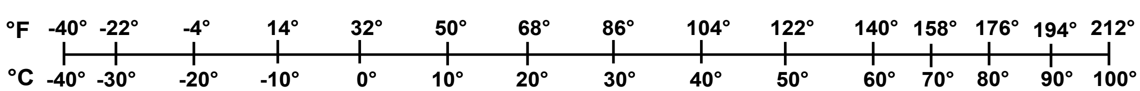

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Executive Summary

The Hybrid III Rail Safety (H3-RS) anthropomorphic test device (ATD) is a crash test dummy that was developed in the UK to evaluate abdomen and lower thorax injuries that occur when passengers impact workstation tables during train accidents. The H3-RS is similar to the standard Hybrid III 50th percentile male ATD used in car crash test regulations and consumer information programs worldwide, but with a more humanlike abdomen response under table-edge loading conditions and with additional instrumentation to measure compression and rate of compression at multiple bilateral locations in the chest and abdomen.

The Transport Research Laboratory (TRL) in the UK tested the biofidelity, repeatability and sensitivity of three abdomen bag designs (designated in the report as designs A, B, and C) in the H3-RS ATD. TRL conducted the series of tests using the eight-wire pendulum impactor facility at its ATD Certification Laboratory. A rigid representation of a steering wheel and a rigid horizontal bar impactor were used, as defined in the National Highway Traffic Safety Administration (NHTSA) biofidelity targets for frontal impact dummies. Additional bar impactors with different mass and bar diameter were also used to evaluate the measurement sensitivity of the ATD. Based on these tests, an abdomen bag design suitable for evaluating the safety of fixed workstation tables in passenger rail cars was selected.

All three abdomen bag designs met the certification requirements for frontal impact dummies. For each design, the upper abdomen biofidelity was very good, while the lower abdomen biofidelity was good and likely could be improved even further.

Since the results of the biofidelity tests showed little difference between the three abdomen designs, TRL chose design B because it provided some coupling between the abdomen and the thorax, which would be more humanlike than having entirely separate abdomen and rib structures. This design will also prevent a workstation table from penetrating between the abdomen and the rib structures and potentially bypassing some of the chest and abdomen deflection transducers. This would ensure the most consistent assessment of the safety of table designs regardless of the vertical position of the table relative to the seat base.

For the selected abdomen bag design B, the upper abdomen showed good repeatability when loaded consistently, but the lower abdomen deflection measurements were found to be asymmetrical, possibly due to damage to one of the sensors. TRL will investigate this further. The H3-RS abdomen bag design B was appropriately sensitive to impact location and velocity, except for lower abdomen velocity sensitivity, which was possibly affected by interaction between the impactor and the pelvis bone of the ATD. TRL will undertake further tests with a narrower impactor to investigate this issue.

1. Introduction

The H3-RS ATD is a crash test dummy developed in the UK to evaluate the safety of passenger train interiors in the event of a train accident. The ATD is particularly useful for evaluating abdomen and thorax injury risk due to impacts with workstation tables during train accidents, as well as assessing the risk of head, neck and leg injuries. Seats and tables are typically evaluated in sled tests, but the dummy has also been used in full-scale passenger train crash tests. This study examines the biofidelity of the H3-RS abdomen (i.e., how humanlike it is), as well as the repeatability and sensitivity of the injury assessment metrics in different loading conditions. Funding for this study was provided by the Federal Railroad Administration (FRA) Office of Research, Development, and Technology via an interagency agreement with the Volpe National Transportation Systems Center (Volpe Center). The Volpe Center contracted with TRL to conduct the tests.

1.1 Background

The H3-RS is similar to the standard Hybrid III 50th percentile male ATD used in automobile crash testing and consumer information programs worldwide, but with a more humanlike abdomen response under table-edge loading conditions and with additional instrumentation to measure compression and rate of compression at multiple bilateral locations in the chest and abdomen.

The H3-RS was designed to meet the biofidelity targets specified by the National Highway Traffic Safety Administration (NHTSA) for the next-generation frontal impact car crash test ATD, called 'THOR,' which stands for Test device for Human Occupant Restraint [1]. The THOR biomechanical response requirements [2] define the response of a human to various loading conditions and help to ensure that the response of an ATD design is humanlike in crash tests. The H3-RS was also designed to meet the certification requirements for THOR [3]. These are tests, based on the biofidelity tests, that every ATD is subjected to on a regular basis to ensure that the ATD continues to perform as it should, and that every ATD of a given type performs in the same way–thereby ensuring reproducible results with different ATDs.

One goal of the testing conducted for this study was to identify an abdomen design that is biofidelic and produces consistent results under a range of impact conditions. If these tests are successful, the ATD abdomen design may be finalized. The FRA and the Volpe Center have an interest in having a finalized H3-RS design because the use of such an ATD is specified for dynamic testing in the U.S. rail safety standard for workstation tables, which is identified as American Public Transportation Association (APTA) PR-CS-S-018-13 – Fixed Workstation Tables in Passenger Rail Cars) [4].

1.2 Objectives

The abdomen impact test series used rigid, linear impactors and an H3-RS ATD. The tests were designed to meet the following objectives:

- To evaluate the accuracy of the current H3-RS abdomen deflection transducers by comparing abdomen deflection time histories using multiple measurement techniques over a range of impact conditions, varying the velocity, impact location, and impactor geometry. Measurement techniques included string potentiometers and double-gimballed string potentiometers (DGSPs) existing within the abdomen of the ATD, as well as photometric analysis of impactor and dummy motion, and integration of impactor accelerometer data.

- To evaluate the biofidelity of different abdomen bag designs by comparing test results to target corridors defined in the THOR-NT biomechanical response requirements document.
- To evaluate test repeatability by conducting multiple tests using the same initial conditions.
- To evaluate sensitivity to variations in impact location, impactor geometry and velocity.

1.3 Overall Approach

TRL provided the H3-RS ATD for use in this test program at its head office in Crowthorne, UK. In addition to the original design, TRL provided two alternative abdomen bags designed to reduce the likelihood of table edges penetrating between the abdomen and the rib cage in a manner not representative of a human occupant. TRL also fabricated rigid impactors to deliver the dynamic load to the abdomen of the H3-RS ATD.

TRL conducted the test program according to the Statement of Work in PR No. DTRT-RVT-61-1046, with minor revisions agreed to by the Volpe Center's project manager for this project. Most of the tests were witnessed by the project manager. All tests utilized the eight-wire pendulum impact rig in the TRL ATD calibration and certification facility.

1.4 Scope

The three abdominal bag designs used in this study, designated as A, B, and C, are described as follows:

A. A design that fills the void between the pelvis, lumbar spine and rib cage
B. A design identical to a), but coupled to the front of the rib cage with hook-and-loop fabric, in a similar manner to the THOR dummy
C. A design identical to a), but extending 20 mm up inside the rib cage to help prevent penetration of narrow table edges between the top of the abdomen bag and the rib cage

The abdomen instrumentation package for all three designs was identical. The test variables included impactor shape, mass and velocity, and impact location.

1.5 Organization of the Report

Section 2 details the test configurations for the different types of test conducted (i.e. biofidelity, repeatability and sensitivity to different impact parameters), the test procedures used and the measurements made. The results are presented in Section 3, with discussion and conclusion in Sections 4 and 5 respectively.

2. Method

This chapter describes the series of abdomen impact tests on the H3-RS ATD under a range of impact conditions. The variables in the test matrix included:

- The impact location
- The velocity of the impactor
- The geometry of the impactor
- The design of the abdomen foam and the bag used to house the foam

Performance of the abdomen deflection transducers and the different abdomen designs were evaluated in terms of biofidelity, repeatability, and sensitivity to the location, velocity, and geometry of the impactor. For the biofidelity assessment, the upper and lower abdomen deformation-time histories and force-deformation histories are compared to the performance targets in the THOR-NT biomechanical response requirements document [2]. The data collected from tests with identical impact conditions are compared to evaluate repeatability. The injury metric data calculated from tests with variable impact location, geometry, and velocity are compared to evaluate the sensitivity of abdomen injury risk predictions to these variables. The deformation measured by the abdominal transducers are compared to the displacement of the impactor to evaluate accuracy of the transducers.

All tests were performed with an eight-wire pendulum impactor, as shown in Figure 1. The face of the impactor is either a rigid, cylindrical bar with a diameter of 25 or 50 mm, or a 27 mm-diameter curved representation of a steering wheel. These impactors are consistent with ATD abdomen biofidelity requirements and certification tests based on cadaver testing.

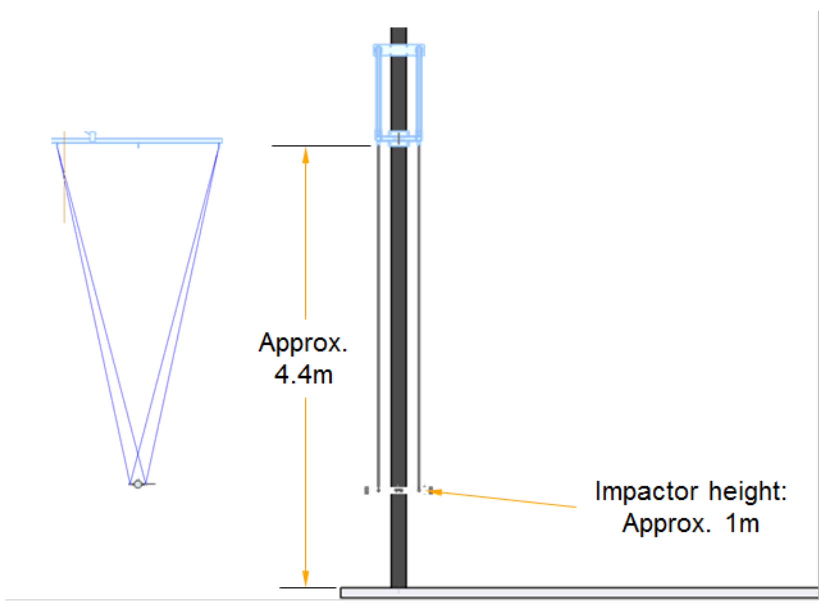

Figure 1. Pendulum impactor arrangement showing approximate length of supporting cables and eight crossed wire attachment

2.1 Test Configurations

A series of impact tests were conducted at the upper and lower abdomen of the ATD. The total mass, impactor geometry, vertical impact location, velocity, and kinetic energy are specified in the section. Figure 2 illustrates the vertical impact location identifications (either aligned with the upper abdominal DGSPs or with the lower abdominal string potentiometers). The ATD also has bilateral tri-axial deflection transducers located in the upper and lower thorax regions shown in Figure 2. In addition to the individual test matrices shown in the following sections, an aggregated test matrix may be found in Appendix A.

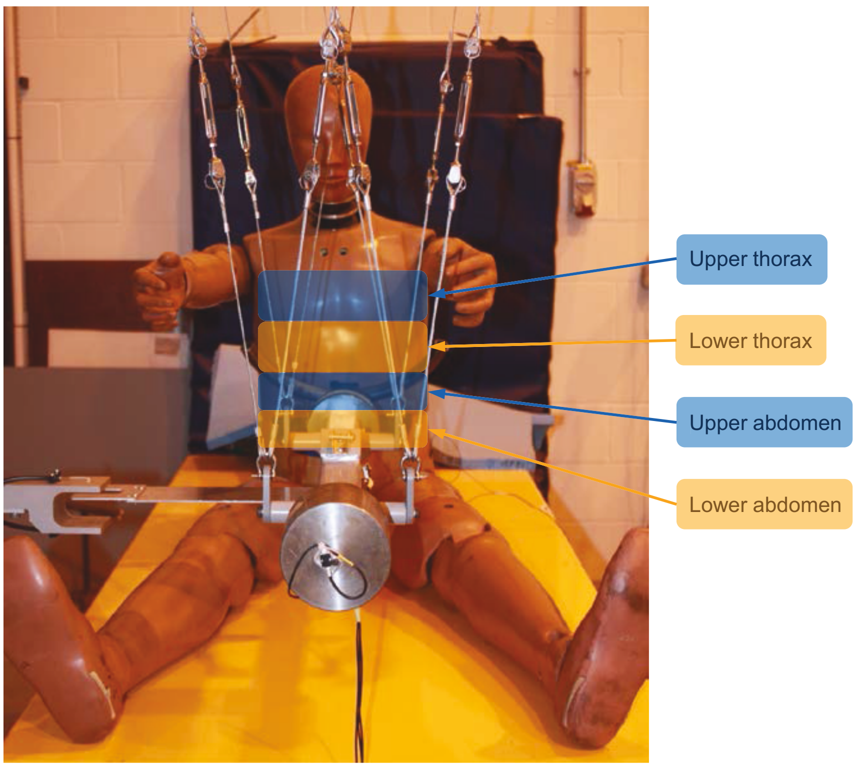

Figure 2. Approximate positions of H3-RS thorax and abdomen body regions

2.1.1 Biofidelity Tests

The first series of impact tests was conducted in accordance with the THOR-NT biomechanical response targets to evaluate the biofidelity of three different abdomen designs. One abdomen design was then selected and used in the remainder of the test program.

Upper abdomen with 26.7 mm steering wheel

These tests are similar to the upper abdomen test in the THOR certification manual (derived from Nusholtz [5] in terms of mass (18 kg), impact location (~L2), and velocity (3.9 to 10.8 m·s^{-1} in the cadaver tests, 8.0 m·s^{-1} specified in THOR-NT biomechanical response requirements). These tests used a steering wheel-shaped impactor, fabricated in accordance with the schematic in Appendix B, Figure B.1. The outer dimension (OD) of the curved bar is 26.9 mm.

The steering wheel is mounted at an angle of 30° with respect to vertical. In the original Nusholtz cadaver tests [5], the height of the impact point was defined with respect to anatomical landmarks. This was converted to the height of the center of the 7th rib when interpreted in the THOR certification manual (GESAC, 2005b). Measurements were made of the TRL THOR ModKit dummy to identify the impact height with respect to a laboratory reference. From these measurements it was established that to match the specification in the THOR certification manual the H3-RS should be tested such that the center of the steering wheel rim, at its lowest point of curvature, is 15 mm above the level of the upper abdomen DGSPs.

The following three abdomen bag designs were tested at this impact location to evaluate their influence on DGSP response:

A. The original design
B. As the original but with one part of a Velcro-like hook-and-loop closure system covering the front of the bag and the lower thorax (in two pieces) and the other part (of a single piece) pressed over that area
C. As the original but modified so that the top of the bag and the foam contained within it extends upwards (superior) to overlap with the bottom rib

Table 1 shows the upper abdomen biofidelity test matrix.

Table 1. Upper abdomen biofidelity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#1	1-1A	A	At DGSP +15 mm	26.7 mm SW‡	18	8.0	576
#4	1-1B	B	At DGSP +15 mm	26.7 mm SW	18	8.0	576
#5	1-1C	C	At DGSP +15 mm	26.7 mm SW	18	8.0	576

‡ Steering Wheel representation

Lower abdomen with 25 mm diameter bar

These tests are similar to the lower abdomen test in the THOR certification manual and are based on the post mortem human surrogates (PMHS) tests reported by Cavanaugh *et al*. [6] in terms of mass (32 kg), impactor shape (25 mm diameter bar), impact location (~L3, or umbilicus), and impactor velocity (4.9 to 7.2 $m \cdot s^{-1}$ in the cadaver tests, 6.1 $m \cdot s^{-1}$ specified in the THOR biomechanical response targets). These tests used a T-shaped bar impactor, made in accordance with the schematic in Appendix B, Figure B.2.

The test was conducted on the three abdomen bag designs (as above), at the vertical location of the string potentiometers, to evaluate their influence on the lower abdomen biofidelity response. Table 2 shows the lower abdomen biofidelity test matrix.

Table 2. Lower abdomen biofidelity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#2	1-2A	A	At string pot	25 mm bar	32	6.1	595
#3	1-2B	B	At string pot	25 mm bar	32	6.1	595
#6	1-2C	C	At string pot	25 mm bar	32	6.1	595

2.1.2 Repeatability Tests

To establish dummy repeatability, two further tests were conducted at the same impact location on the upper and lower abdomen.

Upper abdomen with 26.7 mm steering wheel

This series of tests was conducted on the selected abdomen design (bag 'B') using the same biofidelity test conditions as in Section 2.1.1. Table 3 shows the upper abdomen repeatability test matrix.

Table 3. Upper abdomen repeatability test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#4*	1-1B	B	At DGSP +15 mm	26.7 mm SW‡	18	8.0	576
#9	4-1A	B	At DGSP +15 mm	26.7 mm SW	18	8.0	576
#10	4-1B	B	At DGSP +15 mm	26.7 mm SW	18	8.0	576

* From Table 1

‡ Steering Wheel representation

Lower abdomen with 25 mm bar

This series of tests was conducted on the selected abdomen design (bag 'B') using the same biofidelity test conditions as in Section 2.1.1. Table 4 show the upper abdomen repeatability test matrix.

Table 4. Lower abdomen repeatability test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#3*	1-2B	B	At string pot	25 mm bar	32	6.1	595
#7	4-2A	B	At string pot	25 mm bar	32	6.1	595
#8	4-2B	B	At string pot	25 mm bar	32	6.1	595

* From Table 2

2.1.3 Impact Location Sensitivity Tests

A series of tests was performed to investigate the sensitivity of the abdomen deflection measurements to impact location (the vertical height of the impactor relative to the instrumentation and structures in the ATD).

Upper abdomen with 25.4 mm diameter bar

The upper abdomen test conditions were as for the biofidelity tests except that:

- The 26.7 mm-diameter steering wheel representation was replaced with a 25.4 mm-diameter cylindrical bar, as this geometry is more representative of a workstation table
- The mass of the bar impactor was reduced to 18 kg, to be consistent with the rest of the upper abdomen impact tests

The baseline alignment was as for the biofidelity tests (DGSP +15 mm), with tests at 25 mm intervals above and below this level. An additional test was also performed with the impactor aligned with the DGSP. Table 5 shows the upper abdomen impact location sensitivity test matrix. The T-shaped bar impactor was made in accordance with the schematic in Appendix B, Figure B.3.

Table 5. Upper abdomen impact location sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#12	2-1B	B	At DGSP +40 mm	25.4 mm bar	18	8.0	576
#11	2-1A	B	At DGSP +15 mm	25.4 mm bar	18	8.0	576
#15	2-1D	B	At DGSP	25.4 mm bar	18	8.0	576
#13	2-1C	B	At DGSP -10 mm	25.4 mm bar	18	8.0	576
#20	2-1E	B	At DGSP -35 mm	25.4 mm bar	18	8.0	576

Lower abdomen with 25 mm diameter bar

The lower abdomen test conditions were as for the biofidelity tests except for the change in the vertical height of the impactor relative to the ATD. One test was performed with the impactor raised 25 mm compared to the baseline alignment (i.e., in-line with the string potentiometers). No test was performed 25 mm below the level of the string potentiometers due to difficulty clearing the leg flesh and the risk of direct contact with the pelvis bone of the ATD. Table 6 shows the lower abdomen impact location sensitivity test matrix.

Table 6. Lower abdomen impact location sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#14	2-2B	B	String pot +25 mm	25 mm bar	32	6.1	595
#7*	4-2A	B	At string pot	25 mm bar	32	6.1	595

* From Table 4

2.1.4 Impactor Thickness Sensitivity Tests

A series of tests was conducted at multiple locations on the upper and lower abdomen, using a 50 mm-diameter bar, which is more representative of the thickness of newer workstation tables than the 25 mm bar or steering wheel impactors. Other than the diameter of the impactor the impact conditions and locations match those in Section 2.1.3. An engineering drawing of the impactor is shown in Appendix B, Figure B.4.

Upper abdomen with 50 mm bar

Table 7 shows the upper abdomen impactor thickness sensitivity test matrix.

Table 7. Upper abdomen impactor thickness sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#18	3-1B	B	At DGSP +40 mm	50 mm bar	18	8.0	576
#17a	3-1A	B	At DGSP +15 mm	50 mm bar	18	8.0	576
#16	3-1D	B	At DGSP	50 mm bar	18	8.0	576
#21	3-1C	B	At DGSP -10 mm	50 mm bar	18	8.0	576

Each test to be compared with the equivalent location test in Table 5

Lower abdomen with 50.8 mm bar

Table 8 shows the lower abdomen impactor thickness sensitivity test matrix in. An engineering drawing of the impactor is shown in Appendix B, Figure B.5.

Table 8. Lower abdomen impactor thickness sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#23	3-2B	B	String pot +25 mm	50.8 mm bar	32	6.1	595
#22	3-2A	B	At string pot	50.8 mm bar	32	6.1	595

2.1.5 Impactor Velocity Sensitivity Tests

Tests were conducted at three impact velocities at the upper and lower abdomen, using a 50 mm-diameter bar. Other than the velocity of the impactor the impact conditions and locations match those in Section 2.1.4.

Upper abdomen with 50 mm bar

Table 9 shows the upper abdomen impact velocity sensitivity test matrix.

Table 9. Upper abdomen impactor velocity sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#17a*	3-1A	B	At DGSP +15 mm	50 mm bar	18	8.0	576
#24	5-1A	B	At DGSP +15 mm	50 mm bar	18	6.0	576
#25	5-1B	B	At DGSP +15 mm	50 mm bar	18	7.0	576

* From Table 7

Lower abdomen with 50.8 mm bar

Table 10 shows the lower abdomen impact velocity sensitivity test matrix.

Table 10. Lower abdomen impactor velocity sensitivity test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#22*	3-2A	B	At string pot	50.8 mm bar	32	6.1	595
#26	5-2A	B	At string pot	50.8 mm bar	32	5.1	595
#27	5-2B	B	At string pot	50.8 mm bar	32	7.1	595

* From Table 8

2.2 Test Procedure

The test setup remained consistent for all types of test. The procedure was as follows:

1. Soak the H3-RS ATD in a controlled environment at a temperature between 20.6° and 22.2°C overnight prior to testing. This test program used a soak environment.
2. Inspect the abdomen foam and the outer covering for wear, tears, or other damage. Prior to assembly the abdomen shall also be inspected for any permanent set.
3. Prepare the dummy with no additional clothing.
    a. The dummy is normally used when wearing long cotton shorts (underwear) and a form-fitting T-shirt. For simplicity and to align with anticipated changes in the THOR certification requirements, this test series was carried out with the ATD wearing no T-shirt and no shorts.
4. Position the dummy on a height adjustable platform, with painted metal surface, which supports the pelvis and legs fully.
    a. For simplicity and to align with anticipated changes in the THOR certification requirements, the ATD was seated on the painted metal surface of the supporting scissor-lift table. This deviates from the original Nusholtz upper abdomen cadaver test conditions [5], which used a plastic sheet ('Visqueen' low density polyethylene sheet) covering the table, with a sheet of Styrofoam between the plastic sheet and the cadaver. Similarly, the original Cavanaugh cadaver tests [6] had a thin plastic sheet covering the table.
5. To position the dummy, stretch the lower extremities horizontally and raise the upper extremities to allow positioning of the torso and impactor. The back of the torso is unsupported.
    a. Both upper and lower limbs were spread slightly to avoid contact with the impactor or its support wires. The shoulder joint friction was set to just maintain the arm position without the need for additional support. See Figure 3 for approximate positioning.

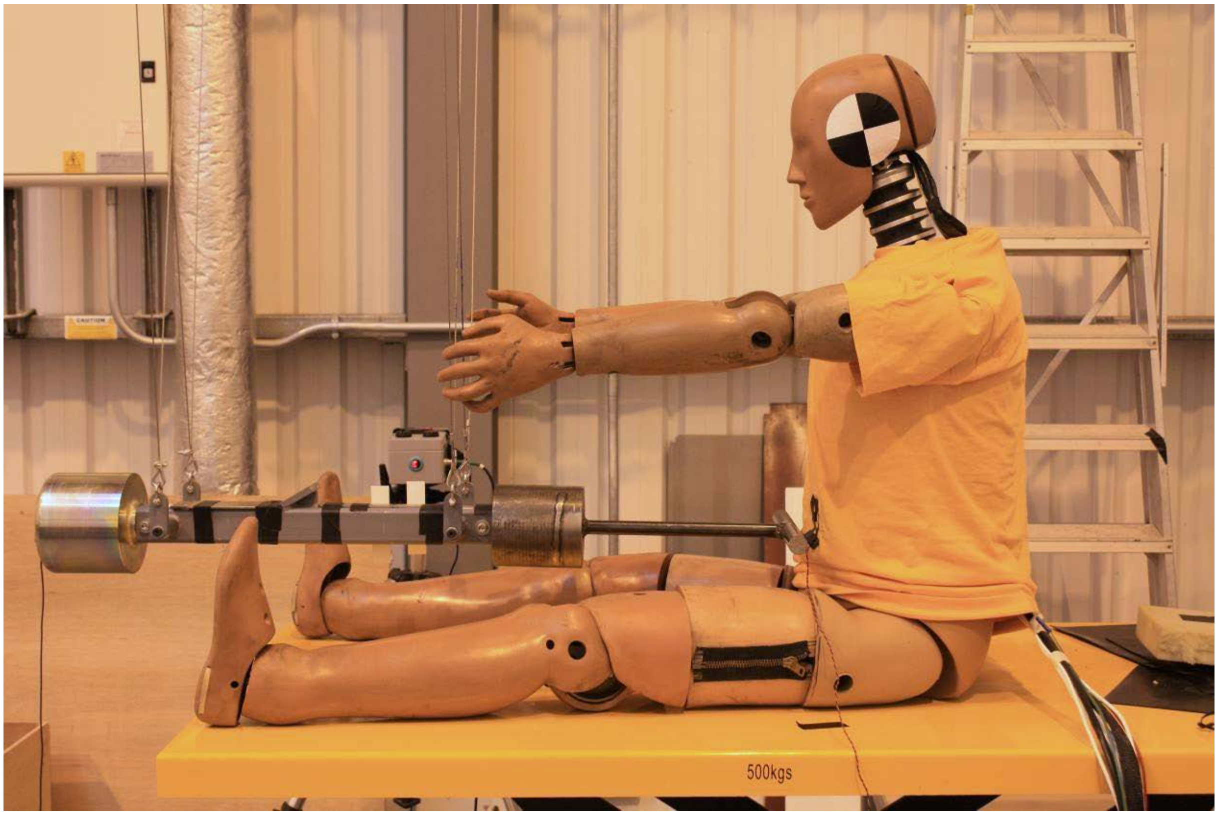

Figure 3. Example dummy position and impactor alignment for lower abdomen biofidelity impact test

6. Adjust the dummy position so that the orientation of the spine (when measured at the height of the impact point) is vertical (+/- 5°).
7. Measure impactor force by recording the impact accelerometer along the axis of the impactor, and multiplying this value by the mass of the impactor.
8. Align the impactor such that it impacts the ATD, normal to the torso, at different vertical locations relative to the upper and lower abdominal transducers, and velocities, per the test matrices defined above.
    a. For each test, a rigid, cylindrical bar (25 or 50 mm nominal diameter, 30 cm in length) or partial steering wheel representation was fitted to the body of the pendulum to give a total mass of 18 or 32 kg. The long axis of the cylindrical bar is perpendicular to the spine (as in Figure 3). The lateral and vertical velocity components of the impactor prior to contact with the ATD were monitored and were less than 0.1 $m \cdot s^{-1}$. For this purpose, two additional uniaxial accelerometers (in addition to the accelerometer aligned with the longitudinal axis of the pendulum) were mounted close to the center of gravity of the impactor to reduce the sensitivity of the measurements to rotations of the impactor.

In addition to this setup procedure, the following features formed the method used throughout the test series:

1. The polarity conventions and data acquisition system conform to requirements of SAE Recommended Practice J211. Data sampling rates were 20,000 samples/second.
2. Position and orientation targets were placed on the end of a rigid bar (in view of the side camera), and mounted to the spine, on the side of the ATD, at the same height as the impact bar.
3. Each test was captured using high-speed (1,000 frames per second) digital cameras providing a frontal view and a side view.
4. Pre-and post-test still digital photographs of the test configuration were taken.
5. The thorax and abdomen instrumentation was visually inspected after each test to ensure that no damage occurred during the test.
6. Prior to each test, the abdomen bag was compressed and extended (pulled forwards) to ensure that the DGSPs and string potentiometers were moving freely and not holding the abdomen foam in compression. Between tests and overnight the string potentiometers and DGSPs were held in their neutral position using a special plate to ensure that the abdomen foams were not compressed by the tension in the string potentiometers.

2.3 Test Measurements

The following test data was measured and documented, and all data was filtered in accordance with SAE J211 Part 1 (2007).

Acceleration time histories (longitudinal, unless otherwise noted):

- Chest (triaxial)
- Spine
- Pelvis
- Rigid impactor (triaxial)

Velocity:

- Velocity of impactor at time of contact. This was measured using a timing gate.
- The off-axis components of velocity were determined through integration of accelerometers aligned perpendicularly to the longitudinal axis of the impactor.

Deflection-time histories from H3-RS instrumentation (CFC180):

- Left and right upper CRUX
- Left and right lower CRUX

- Left and right DGSP transducers
- Left and right string potentiometers

Longitudinal displacement-time histories of the rigid impactor:

- By video analysis
- By integration of impactor accelerometer

Longitudinal displacement-time histories of the ATD target:

- By video analysis

Forces:

- Impact force-time history at contact face

This was obtained by measuring the acceleration at the back of the pendulum and the relationship:

$$F=ma$$

where: F is the force to be assessed

m is the mass of the impactor

a is impactor acceleration

3. Results

3.1 Biofidelity

The H3-RS and THOR abdomen biofidelity targets are defined in terms of the external force-deflection response. For this test series, the deflection was based on impactor and lumbar spine acceleration measurements. This data was cross-checked against external deflection measurements derived from markers placed on the impactor and the lumbar spine of the dummy (which replicated the method used in the original cadaver tests) and the two approaches were found to be comparable. The graphs in this section also show the force-deflection response in terms of the internally measured deflection (DGSP X-axis deflection or string potentiometer change of length), compared with the certification requirements for the H3-RS and THOR abdomen.

Upper Abdomen

All three abdomen bag options met the THOR certification requirement (internal deflection, measured in the H3-RS by the upper abdomen DGSPs). Bag 'B' was a slightly better match for the biofidelity target corridor (using external deflection derived from impactor and dummy marker tracking), being almost entirely within the corridor between 45 and 110 mm of external deflection, although the difference between the bag options does not appear to be significant in the context of the test-to-test variation. It should be noted that the THOR-NT biomechanical specification document (GESAC, 2005a) does not provide guidance on interpreting test results that do no fall entirely within the corridor, and that more than half of the PMHS were outside of the corridor for at least part of the deflection (up to 120 mm deflection). Figure 4 shows certification and biofidelity results, together with the certification requirement box and the biofidelity response corridor.

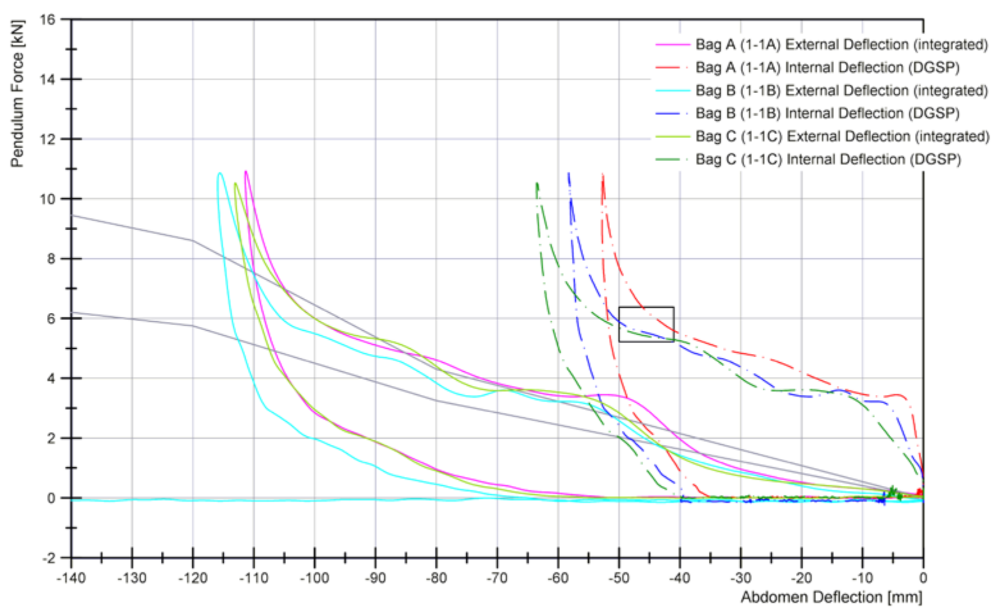

Figure 4. Upper abdomen internal and external biofidelity results, steering wheel impactor

Lower Abdomen

In the lower abdomen biofidelity tests, abdomen bags 'A' and 'B' gave similar responses, as shown in Figure 5. Bag 'C' was within the biofidelity corridor until approximately 85 mm of external deflection, compared with approximately 75 mm for bags 'A' and 'B'. In the repeat tests with bag 'B' (see Section 2.1.2 and Figure 6), the force-deflection response remained within the corridor up to 75 and 80 mm. The internal-force deflection measurement was also better aligned with the center of the certification box, not clipping the outside corner as it does in Figure 5.

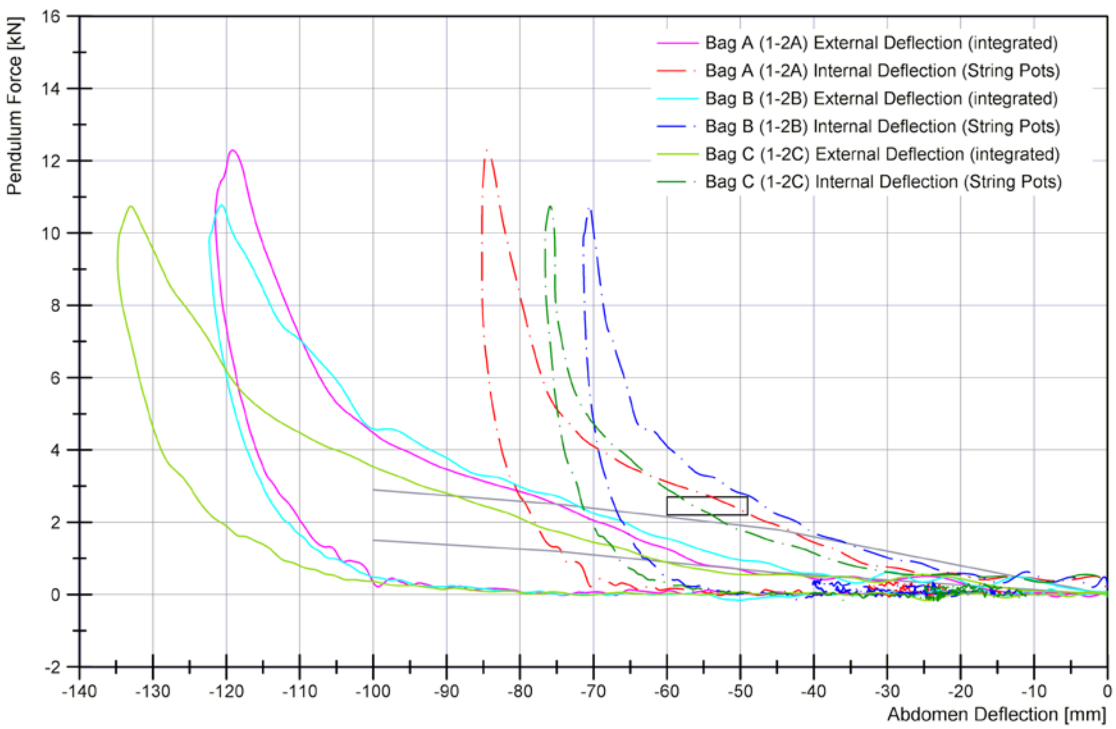

Figure 5. Lower abdomen internal and external biofidelity results, 25 mm bar impactor

Given that the performance of all three abdomen bag designs was comparable in meeting the biofidelity (and certification) targets additional attributes were considered in selecting a design for evaluation in the remaining tests. After a review of the biofidelity results and discussion with the COR, bag design 'B' was selected for the remainder of the test program. This bag design was considered to be the most appropriate because coupling the abdomen to the ribs would be more humanlike than having entirely separate abdomen and rib structures, and because it would make it extremely unlikely that a table could bypass the abdomen transducers by penetrating between the abdomen bag and the ribs, which would be a non-humanlike behavior. A similar approach is used in the THOR-NT design, where the upper abdomen bag is attached directly to the lower three ribs, and the lower abdomen bag is coupled to the upper abdomen bag using a hook-and-eye system. Furthermore, the jacket of the THOR-NT dummy features a crotch strap that prevents the jacket from riding up, which will help prevent penetration between the rib cage and the abdomen.

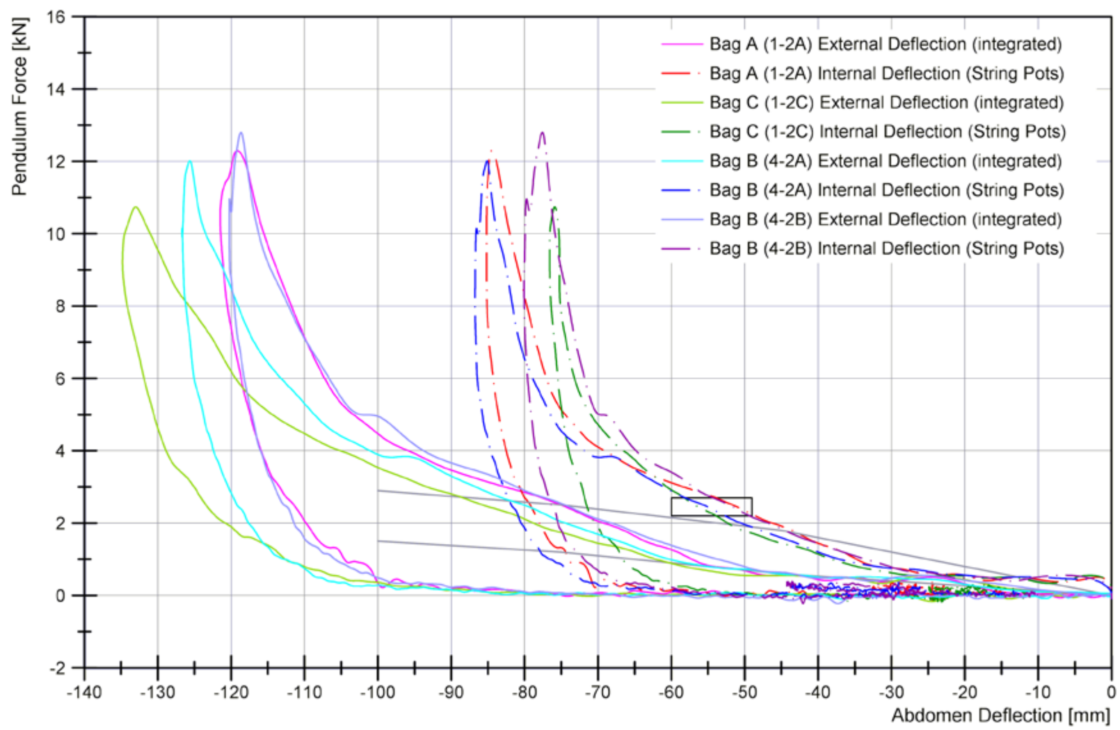

Figure 6. Lower abdomen internal and external biofidelity results from repeatability tests with abdomen bag 'B'

3.2 Repeatability

Upper Abdomen

Figure 7 shows the maximum upper abdomen deflection results of three repeat tests to the upper abdomen using the steering wheel impactor and Figure 8 shows the internal and external force-deflection responses in the same tests. The repeatability of the maximum mean deflection and of the force-deflection response was very good, as were the left and right deflections in tests 4-1A and 4-1B. However, the left and right deflections in test 1-1B were asymmetrical (as shown in Figure 7), with the left deflection being 10 mm greater than the mean and the right deflection being 10 mm less than the mean. Inspection of the high-speed film of test 1-1B showed that the impactor rebounds asymmetrically, twisting to the dummy's left. The pre-test photographs indicate that the torso of the dummy is leaning slightly to the right such that while the impactor is aligned with the center of the abdomen, the upper edge of the steering wheel is slightly offset relative to the rib cage. It is possible that, as a result, the upper part of the steering wheel profile had increased interaction with the ribs on the dummy's right side, and less interaction with the ribs on the dummy's left side. This would effectively reduce the resistance to the impactor on the left side and allow greater penetration of the impactor.

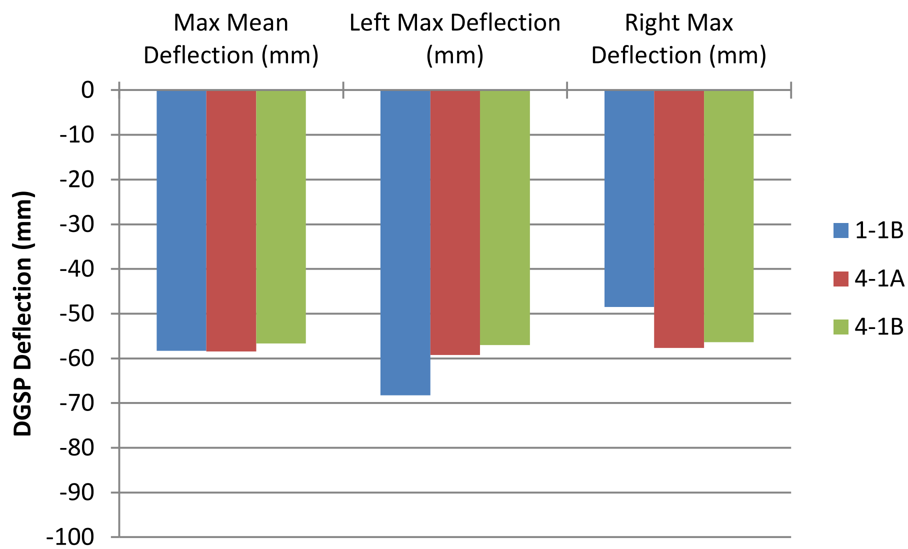

Figure 7. Repeatability of upper abdomen deflection measurements – maximum X-axis deflection measured by the DGSPs

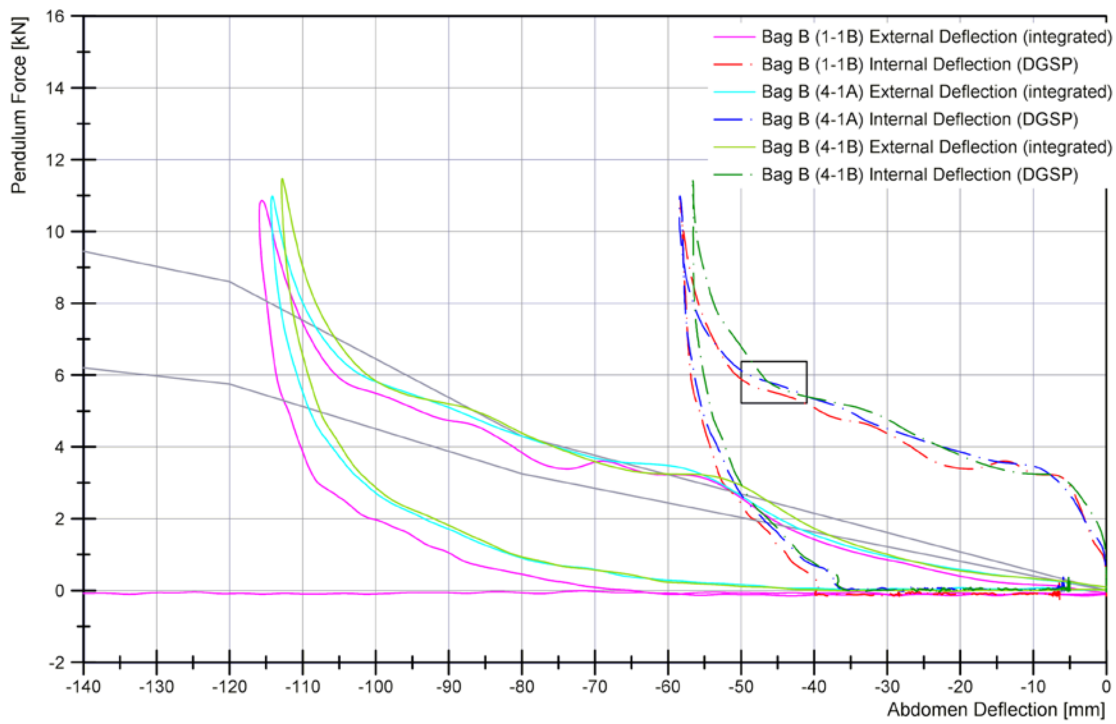

Figure 8. Repeatability of upper abdomen deflection measurements – internal and external force-deflection

Figure 9 shows the repeatability of the upper abdomen VC measurements, which shows a very similar pattern to the deflection results in Figure 7.

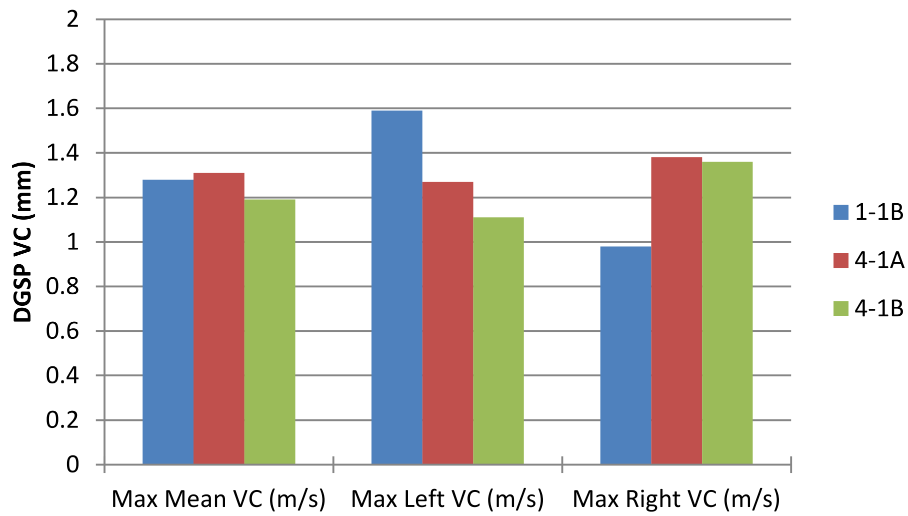

Figure 9. Repeatability of the upper abdomen VC measurements

Lower Abdomen

Figure 10 and Figure 11 show the maximum lower abdomen deflections and force-deflection responses respectively. The results of tests 4-2A and 4-2B are comparable, but test 1-2B shows a markedly lower maximum deflection measurement, even though the external deflection (shown in Figure 11) for this test was comparable to that of the other two tests. Inspection of the high-speed video indicated that test 1-2B has the impactor slightly lower (approximately 10 mm) relative to the chest and pelvis flesh, and therefore presumably the lower abdomen instrumentation. This may explain the lower maximum mean deflection measured by the internal instrumentation.

No asymmetry in the response of the dummy or of the impact or rebound of the pendulum was observable in the high-speed film. However, the left and right deflection in all three tests is notably asymmetrical (Figure 10). Despite the differences in total mean deflection these tests show a similar pattern of asymmetrical deflection, with the right string potentiometer measuring more deflection than the left.

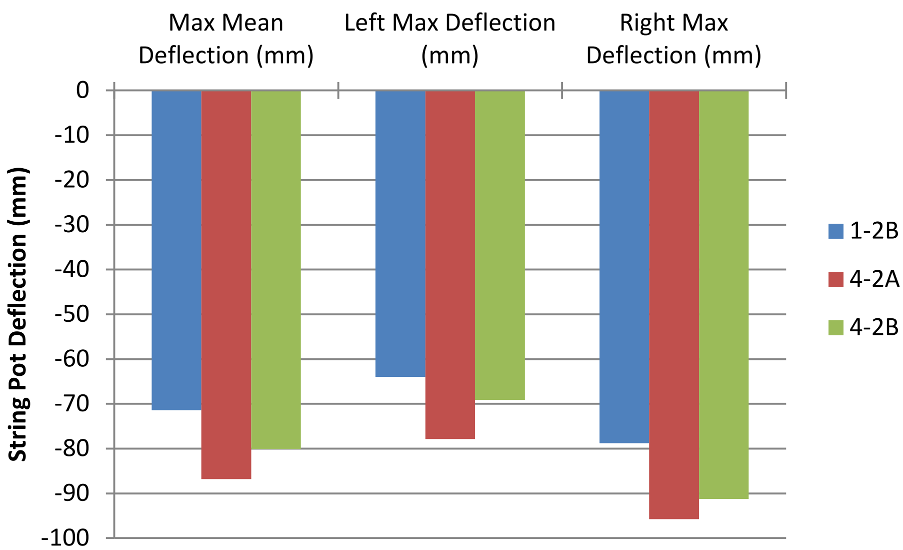

Figure 10. Repeatability of lower abdomen deflection measurements – maximum deflection measured by the string potentiometers

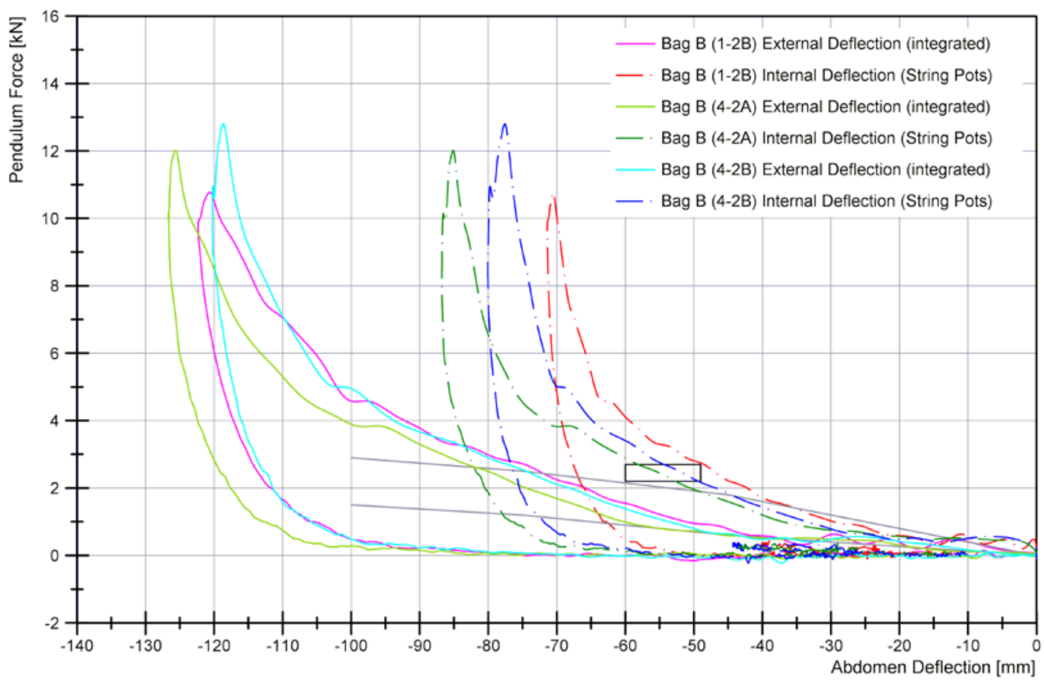

Figure 11. Repeatability of lower abdomen deflection measurements – internal and external force-deflection

Figure 12 shows the repeatability of the lower abdomen VC measurements, which shows a similar pattern to the deflection measurements in Figure 10.

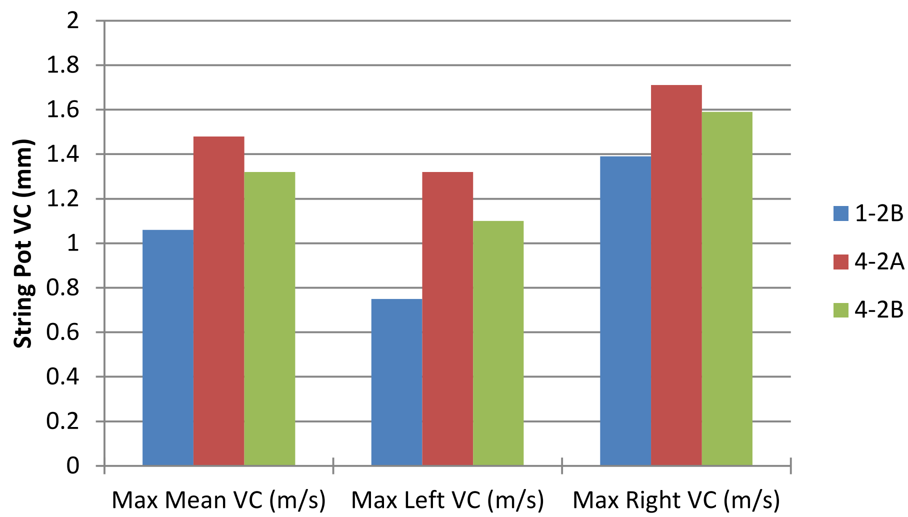

Figure 12. Repeatability of the lower abdomen VC measurements

3.3 Impact Location and Impactor Thickness

Upper abdomen

With both the 25 mm bar (Figure 13) and the 50.8 mm bar (Figure 14) there is a marked sensitivity of the upper abdomen deflection measurement to impact location, with the maximum deflection occurring for impacts directly in line with the DGSP sensor and decreasing as the distance above or below the DGSP increases.

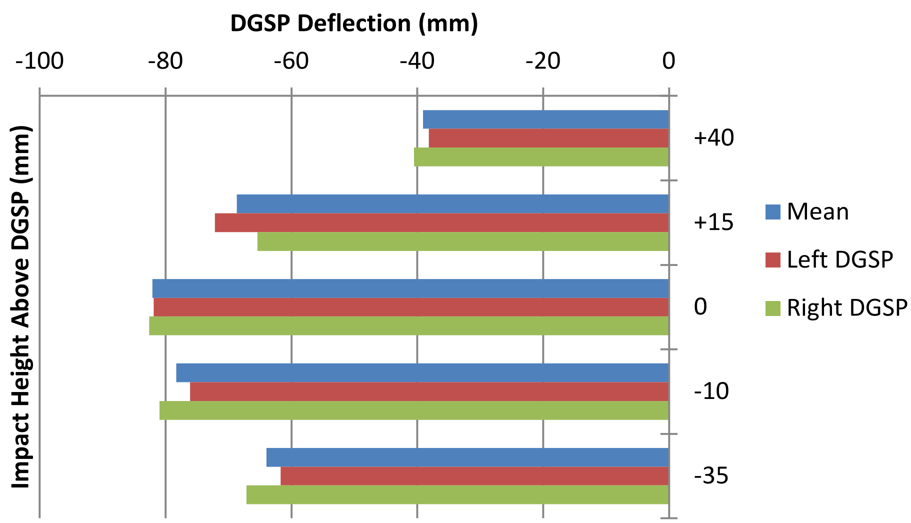

Figure 13. Upper abdomen impact location deflection sensitivity results with 25 mm diameter bar impactor

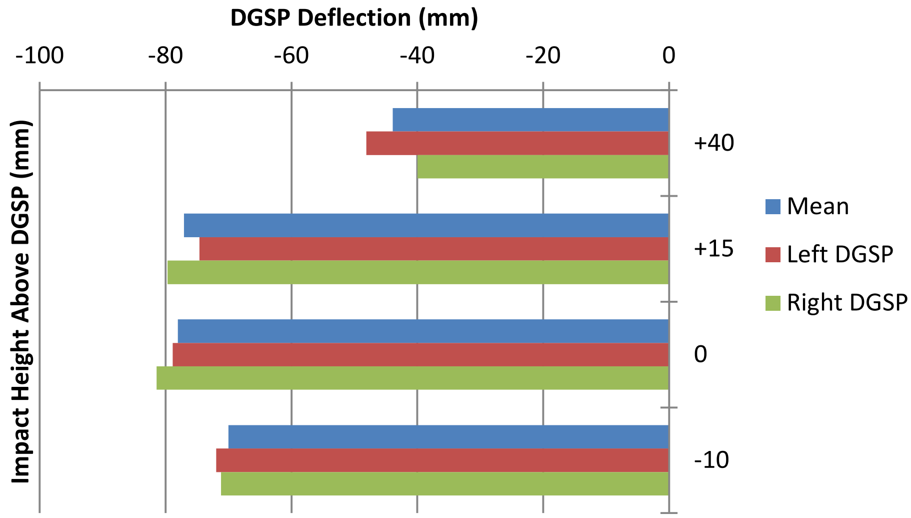

Figure 14. Upper abdomen impact location deflection sensitivity results with 50.8 mm diameter bar impactor

However, this is largely compensated for by a transfer of the loading to other sensors. Figure 15 shows the mean upper abdomen deflection for both sizes of bar impactor (the blue bars from Figure 13 and Figure 14), while Figure 16 shows the maximum deflection measured at any point (lower abdomen, upper abdomen, lower chest or upper chest). It is clear that while less deflection is measured at the upper abdomen as the impact site moves away from the DGSP, other sensors are picking up the loading. For example, for an impact with a 25 mm bar 40 mm above the DGSP, the upper abdomen deflection measurement was approximately 40 mm, while for the same impact the lower chest deflection was 64 mm. Note that the lower chest deflection at this impact point would not be expected to be identical to the abdomen deflection in the impact at the DGSP: the stiffness and the effective mass of the dummy change with impact location, as they would for a human occupant.

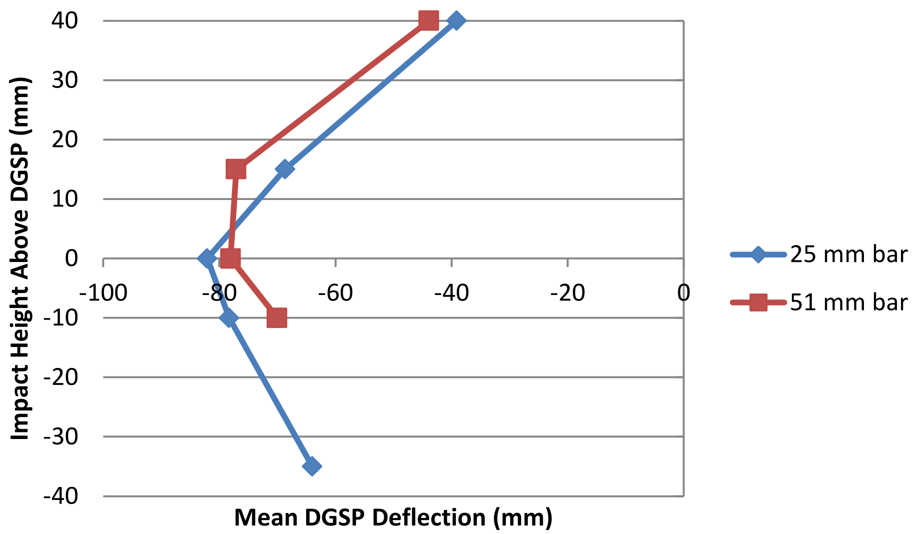

Figure 15. Impact location sensitivity results – mean upper abdomen DGSP deflection

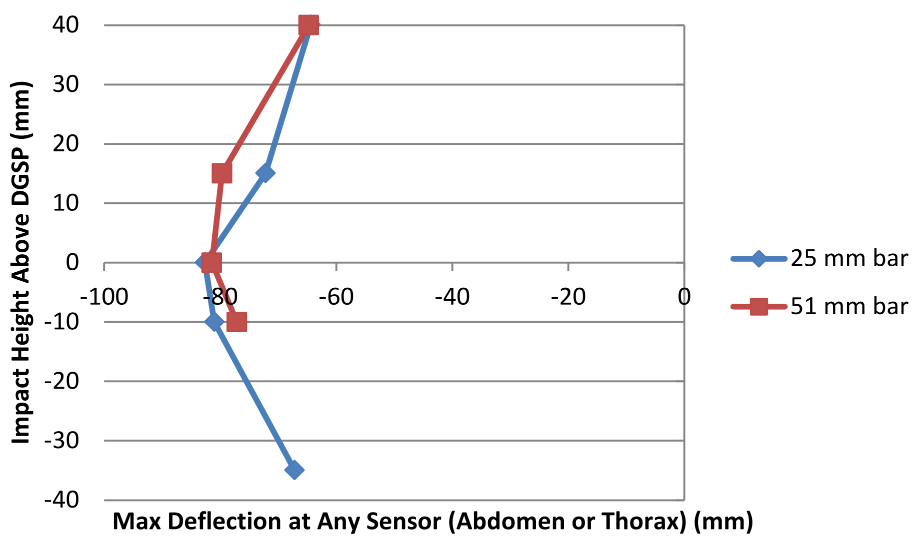

Figure 16. Impact location sensitivity results maximum abdomen and thorax deflection

Figure 17 shows the variation in DGSP VC measurement with impactor height relative to the DGSP, for impacts with the 25 mm diameter bar. It is notable that the mean value is not central to the left and right measurements, because the maxima of the individual channels do not occur at the same time. The pattern of variation in VC is similar to that for deflection (Figure 13), although the VC is more sensitive to impact alignment than is the deflection measurement.

Figure 18 shows the maximum VC measured at any abdomen or thorax sensor for each impact height. This shows a somewhat more consistent assessment of VC than using the DGSP measurements alone. However, the maximum VC in the impact 40 mm above the DGSP sensor was recorded at the lower thorax instrumentation, which has a lower threshold of 1.0 $m \cdot s^{-1}$

compared with 1.98 m·s^{-1} at the abdomen sensors. Normalizing the VC by the threshold for the sensor that recorded the maximum value gives a very even response across the different impactor heights, especially with the larger diameter impactor (Figure 19).

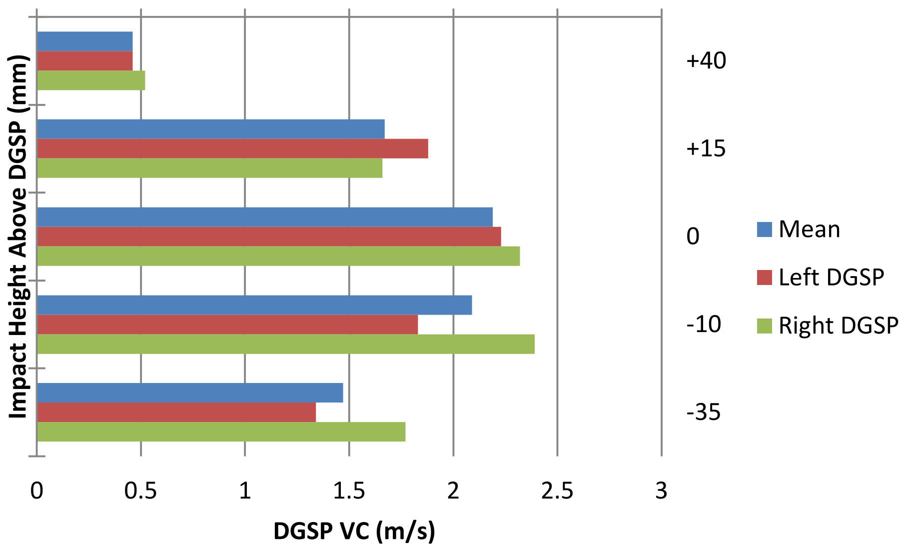

Figure 17. Upper abdomen impact location VC sensitivity results with 25 mm diameter bar impactor

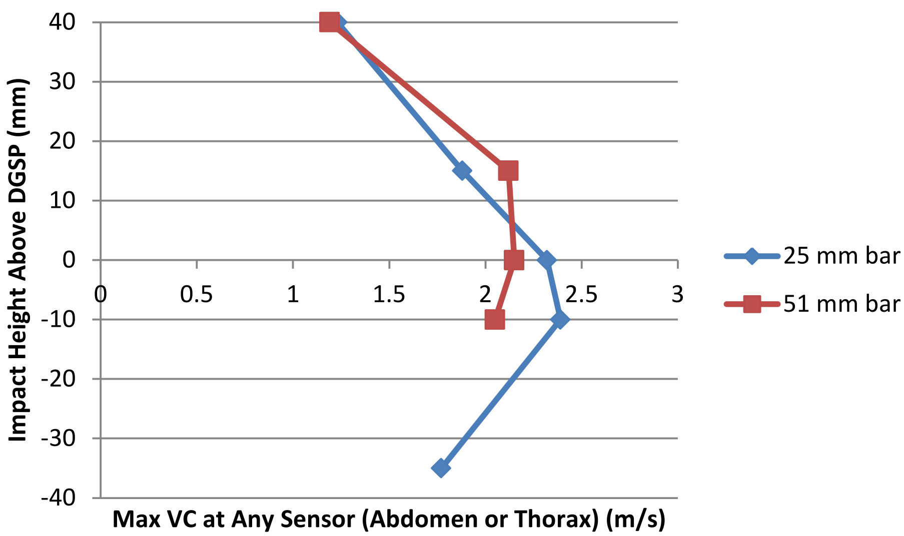

Figure 18. Impact location sensitivity results maximum abdomen and thorax VC

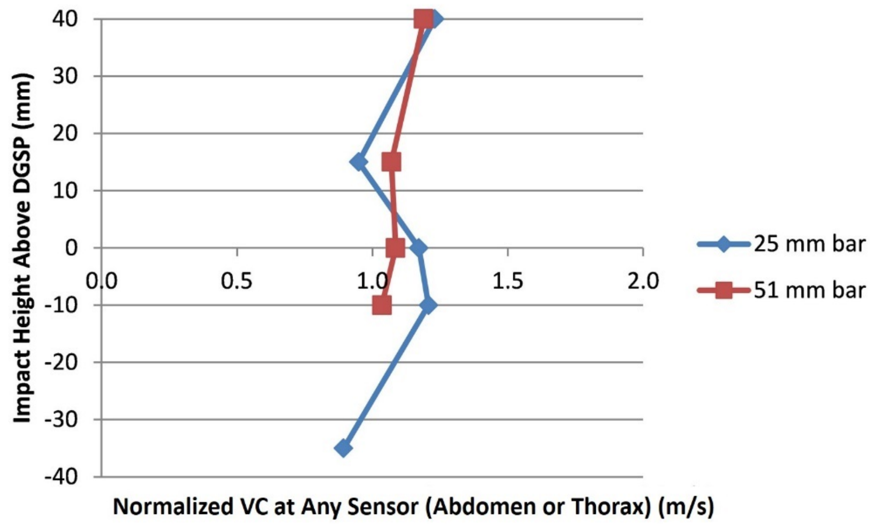

Figure 19. Impact location sensitivity results – normalized maximum abdomen and thorax VC

Lower abdomen

Figure 20 and Figure 21 show the variation in lower abdomen deflection measurement for an impact directly over the string potentiometer measurement location and 25 mm above this point, for 25 mm and 50 mm diameter impactors respectively. The results with the 25 mm bar are as expected, with a lower deflection measured when the impactor is offset from the sensor. However, with the 50 mm bar the results are opposite to this. Review of the high-speed film of the test showed that the impactor was slightly low relative to the sensor (in the test where the impactor and sensor should have been aligned) and therefore there was engagement with the front of the pelvis flesh and likely also some engagement with the top of the iliac wing. Both the offset from the level of the string potentiometer and the engagement with the pelvis flesh and iliac wing will have off-loaded the deflection measurement to some extent.

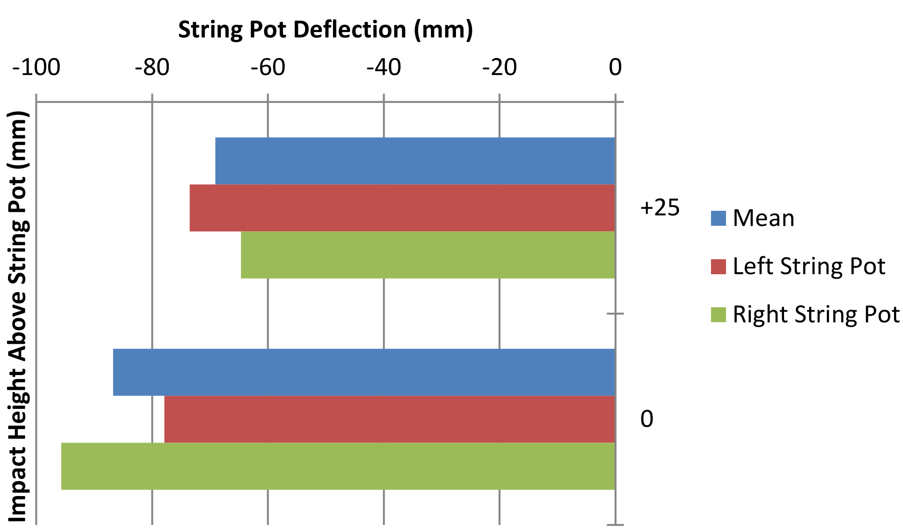

Figure 20. Lower abdomen impact location sensitivity results with 25 mm diameter bar impactor

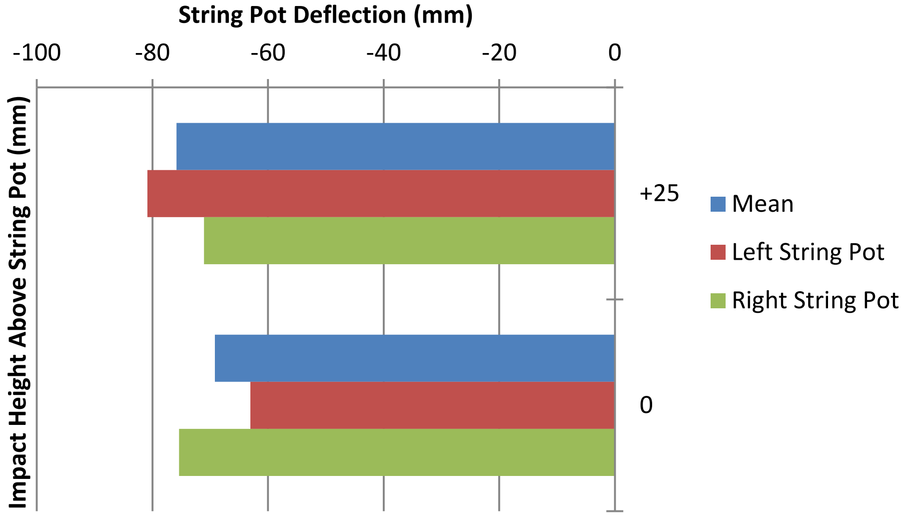

Figure 21. Lower abdomen impact location sensitivity results with 50 mm diameter bar impactor

3.4 Impactor Velocity

Upper Abdomen

Figure 22 shows the maximum DGSP deflection measurements at nominal impact velocities of 6, 7 and 8 $m \cdot s^{-1}$, and Figure 23 shows the VC measurements for the same tests. The results show the expected response, with increasing deflection for increasing impactor velocity. The lower abdomen, external deflection and VC measurements (not shown) in these tests also show the same pattern, although the absolute values of the lower abdomen deflection are lower.

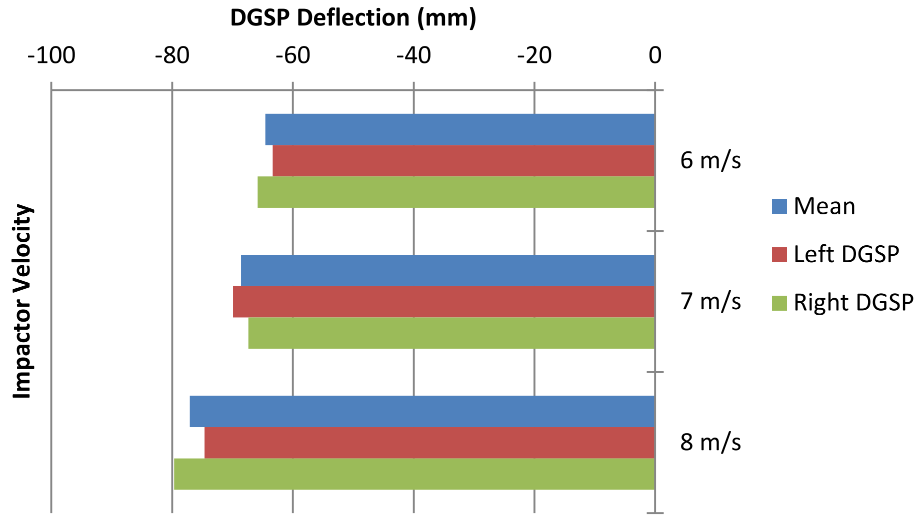

Figure 22. Velocity sensitivity of the upper abdomen deflection measurement with 18 kg, 50 mm diameter bar impactor

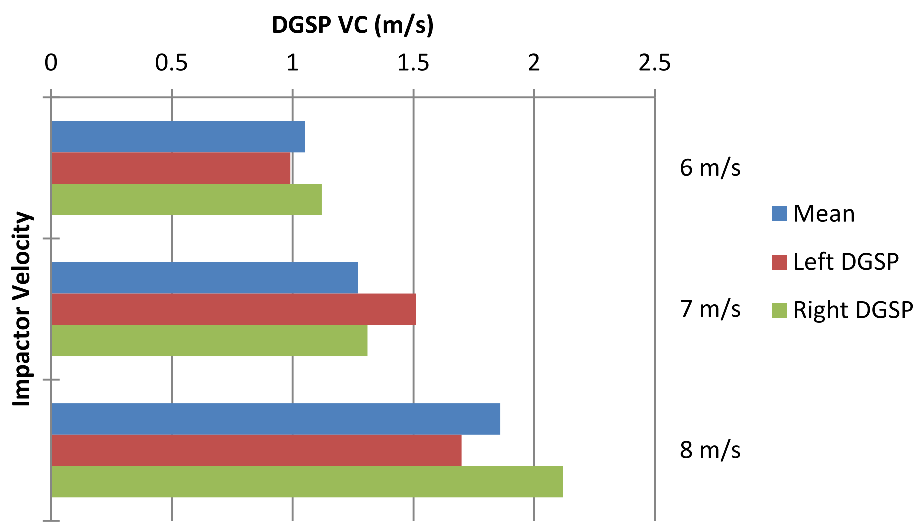

Figure 23. Velocity sensitivity of the upper abdomen VC measurement with 18 kg, 50 mm diameter bar impactor

Lower Abdomen

The lower abdomen string potentiometer deflection measurements at 5, 6 and 7 $m \cdot s^{-1}$ are shown in Figure 24. These do not follow the expected pattern with changing velocity, although the external deflections (also shown in Figure 24) do show the expected increasing deflection with increasing velocity. The VC measurements show a similar pattern (Figure 25). This may be due to interference between the impactor and the iliac wings, as discussed in Section 3.3.

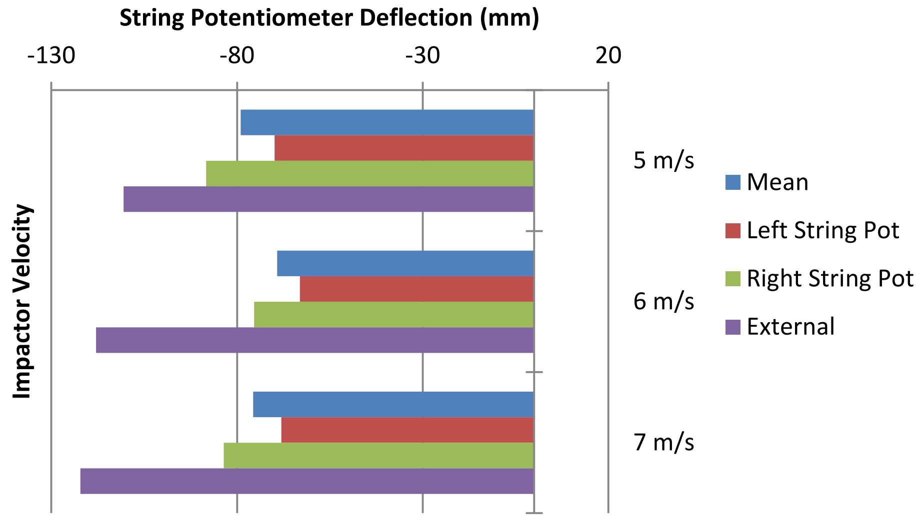

Figure 24. Velocity sensitivity of the lower abdomen deflection measurement with 32 kg, 50.8 mm diameter bar impactor

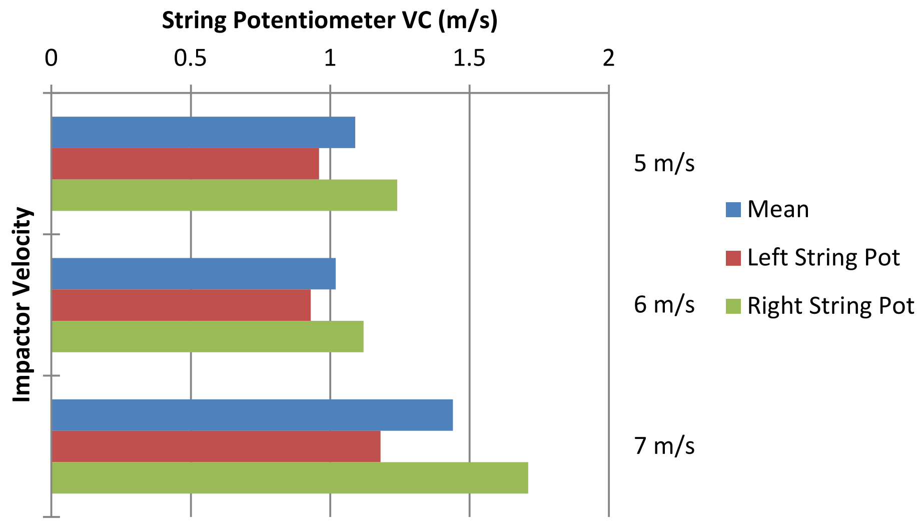

Figure 25. Velocity sensitivity of the lower abdomen VC measurement with 32 kg, 50.8 mm diameter bar impactor

4. Discussion

4.1 Biofidelity

Upper abdomen

The upper abdomen biofidelity target for the H3-RS is identical to that for the THOR-NT dummy, which is based on six PMHS tests undertaken by Nusholtz and Kaiker (1994). There is no information in the original reference regarding the injuries sustained by the six PMHS in the test series on which the biofidelity target is based. The biofidelity test involves impacting the upper abdomen with a rigid steel representation of the lower edge of a steering wheel. It should be noted that the lateral aspects of the steering wheel also interact with the lower ribs, both in the original PMHS tests and with the THOR-NT and H3-RS.

Figure 26 shows the biofidelity response of the H3-RS (solid lines), which can be compared with the response of the THOR-NT in three repeat tests shown in Figure 27. Figure 26 also shows the certification response (dashed lines), compared with the certification requirement (the black box), which is identical for the THOR-NT and H3-RS. The response of both dummies is similarly low in the first 25 mm (THOR) or 40 mm (H3-RS) of the impact, with a slightly stiffer response from 50-70 mm (H3-RS) and 40-60 mm (THOR-NT). The H3-RS is then within the corridor until approximately 105 mm, compared with up to 90 mm for the THOR-NT. By this metric, the biofidelity of the upper abdomen of the H3-RS is slightly improved compared to the THOR-NT, with a good response across a wider compression range.

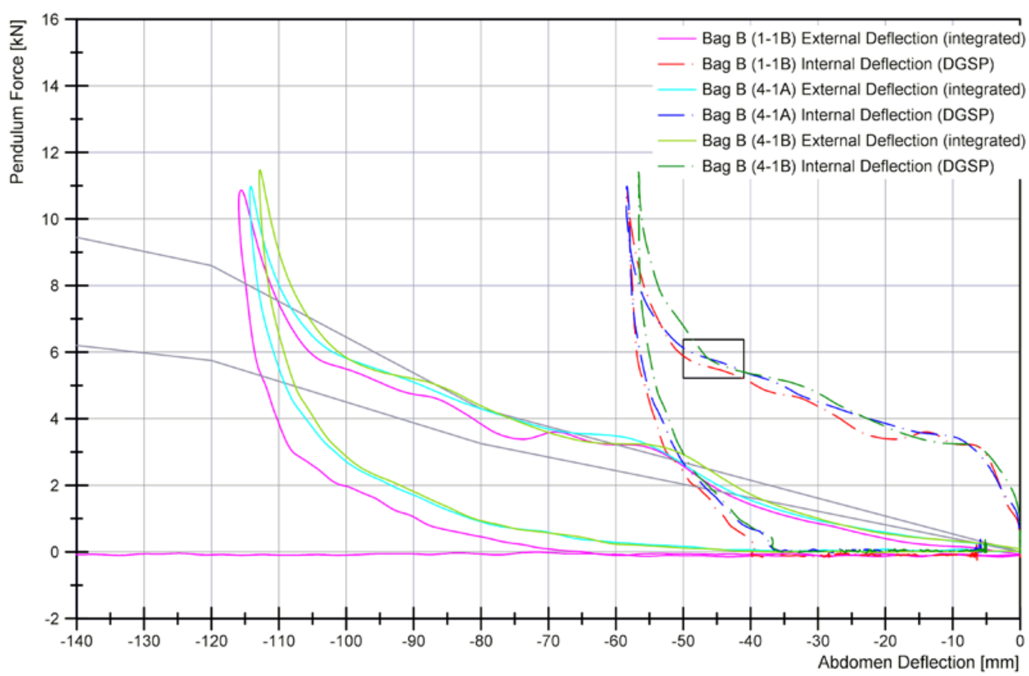

Figure 26. Upper abdomen biofidelity response of the H3-RS – three repeat tests (solid lines) and the biofidelity target corridor (in grey). NB: the certification response in the same tests is also shown (dashed lines) cf. the certification requirement (black box)

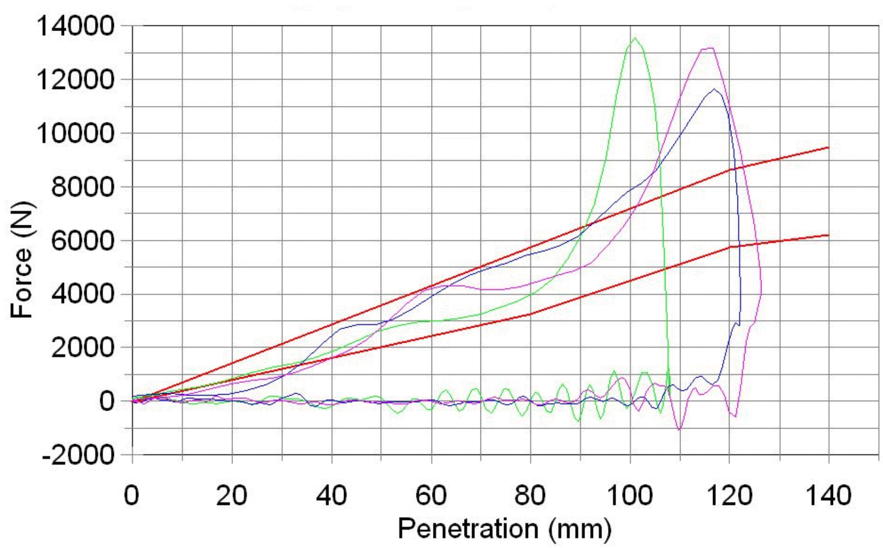

Figure 27. THOR-NT upper abdomen biofidelity test response; three repeat tests (GESAC, 2005a)

The stiffer response of both dummies compared to the PMHS at high deflections is because the spine of both dummy designs occupies a greater percentage of the abdomen depth than the human spine does.

It is clear that there is a difference between the internal and external deflections. The main difference is due to the curvature of the abdomen and of the steering wheel, which are curved in opposite directions. The abdomen deflection transducers are mounted towards the left and right sides of the abdomen, and are therefore set back from the forward-most, central part of the abdomen – which mimics the curvature of the human abdomen. Together with the steering wheel, this accounts for nearly 30 mm of the difference between the internal and external measurements, with the center of the steering wheel loading the center of the abdomen before engaging with the DGSPs. A further 10 to 13 mm is accounted for by the fact that the impact in the biofidelity test is offset vertically from the location of the sensor (see Figure 13).

Lower abdomen

The lower abdomen biofidelity target for the H3-RS is also identical to that for the THOR-NT dummy, and is based on five PMHS tests reported by Cavanaugh *et al.* [6]. One subject sustained an Abbreviated Injury Scale (AIS) 4 liver injury that was attributed to pre-mortem degeneration of the liver and the other four subjects had no observed injury on autopsy. Therefore, despite their apparent severity, the tests are considered to be representative of non-injurious loading – although it is possible that soft tissue abdomen injuries would be less likely to be generated in post mortem subjects than living passenger train occupants, and it is generally considered that soft tissue injuries are more difficult to detect from PMHS tests than bone fractures.

Figure 28 shows the biofidelity response of the H3-RS, which can be compared with the THOR-NT response in Figure 29. The certification response of the H3-RS is also shown in Figure 28 (dashed lines). The H3-RS is within the corridor up to approximately 75 to 80 mm of external deflection, compared with 85 mm for the THOR-NT. Thereafter, the stiffness of both dummies increases in a similar manner. It is likely that this could be fine-tuned in the H3-RS by adjusting the geometry of the abdomen foams, to give a response within the corridor at least up to the deflection level of the THOR-NT.

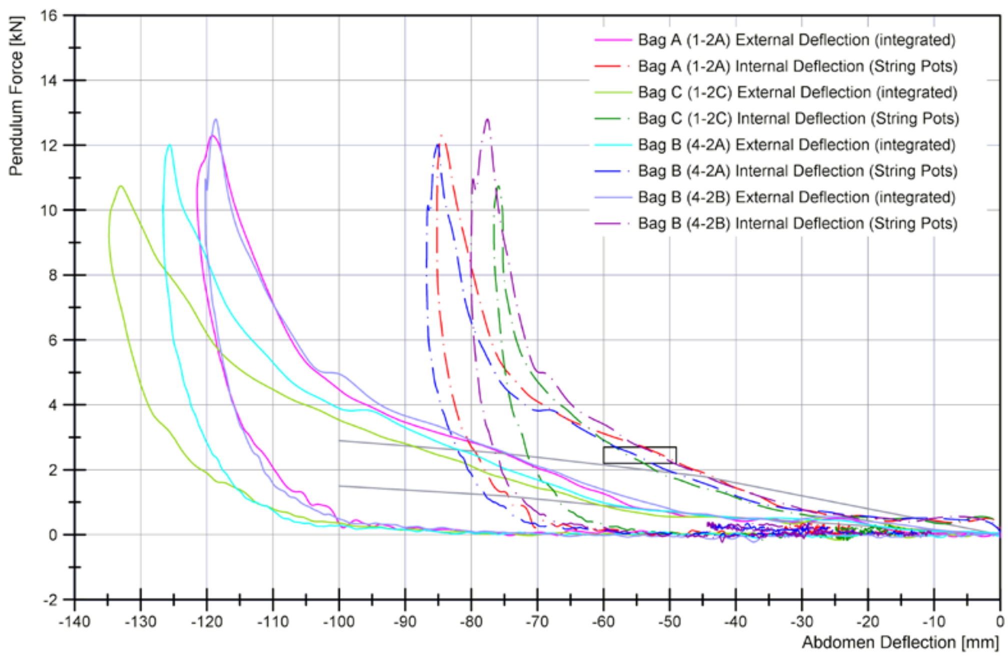

Figure 28. Lower abdomen biofidelity response of the H3-RS– three repeat tests (solid lines) and the biofidelity target corridor (in grey). NB: the certification response in the same tests is also shown (dashed lines) as are the certification requirement (black box)

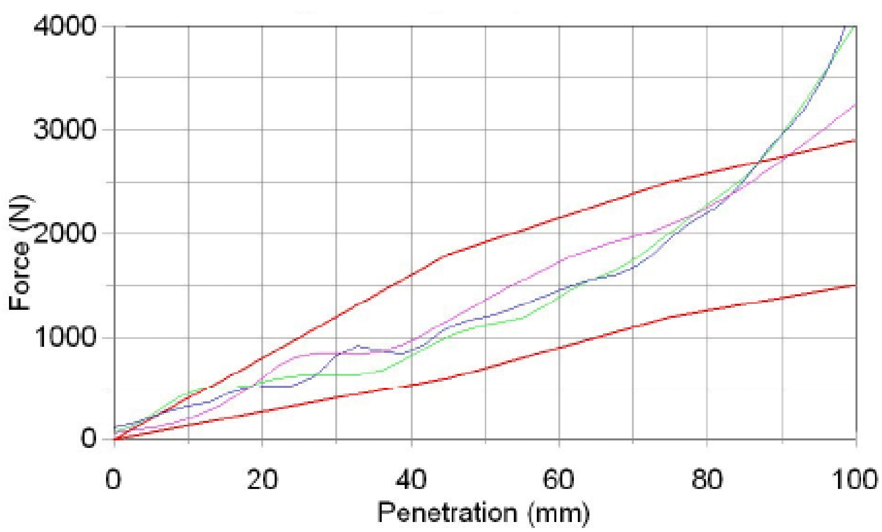

Figure 29. THOR-NT lower abdomen biofidelity test response (GESAC, 2005a)

The difference between internal and external deflection is about 10 mm less than at the upper abdomen. This is because a flat bar is used at the lower abdomen, not the curved steering-wheel representation used for the upper abdomen biofidelity test.

4.2 Repeatability

The repeatability of the upper abdomen biofidelity response was excellent, as shown in Figure 8. The individual left and right DGSP measurements and the derived VC were also repeatable and symmetrical, except for a few tests where there was variation in the alignment of the dummy with the impactor – either a lateral offset, causing an uneven overlap with the curvature of the steering wheel impactor, or a rotation of the dummy about the vertical axis such that it was facing slightly to one side. In these few instances, the asymmetry of the measured deflections reflected the asymmetry of the impact. In this way it can be concluded that the upper abdomen is both repeatable and sensitive to the applied loading.

The lower abdomen deflection response was also repeatable given that one of the impacts was slightly offset from the sensor. However, in the repeatability tests and in subsequent tests the string potentiometer measurements were notably asymmetrical. Figure 30 shows the results of seven impacts to the lower abdomen with a 32 kg bar impactor with a diameter of 25 or 50 mm. Five of the tests show a marked left-right asymmetry, with the right string potentiometer showing a much larger deflection than the left. A similar pattern is seen for the VC in Figure 31. As an example, Figure 32 shows the force-time response from the first of these tests. There is a slight delay in the start of the left deflection response, and the response flattens-off between 70 and 80 mm, compared with a maximum of nearly 100 mm at the right-hand sensor. The two tests highlighted in orange were performed 25 mm above the string potentiometer, and don't show the same asymmetry.

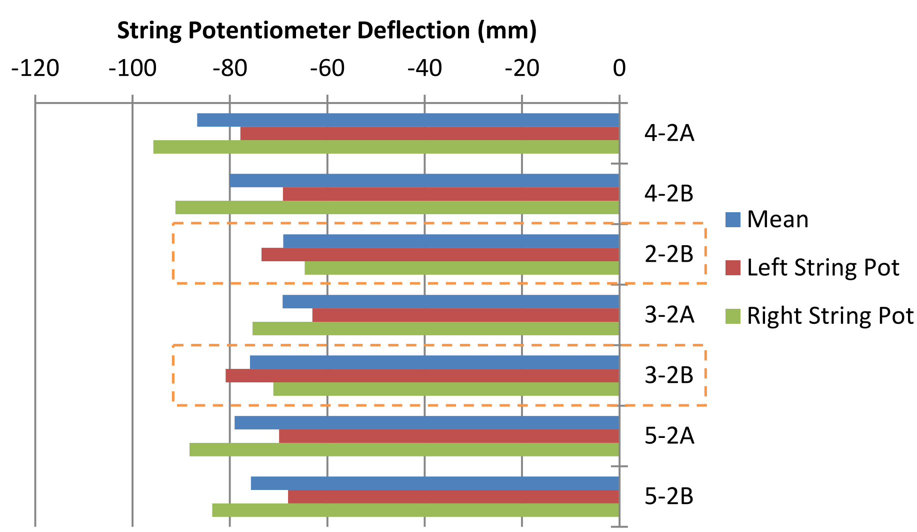

Figure 30. Asymmetry of lower abdomen deflection measurements (dotted boxes highlight tests aligned 25 mm above the string potentiometer; all other tests aligned with the string potentiometer)

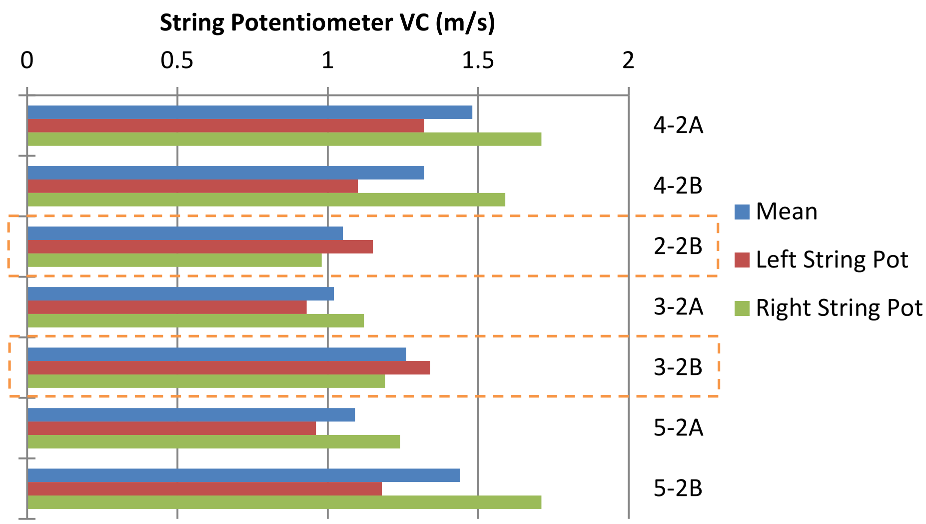

Figure 31. Asymmetry of lower abdomen VC measurements (dotted boxes highlight tests aligned 25 mm above the string potentiometer; all other tests aligned with the string potentiometer)

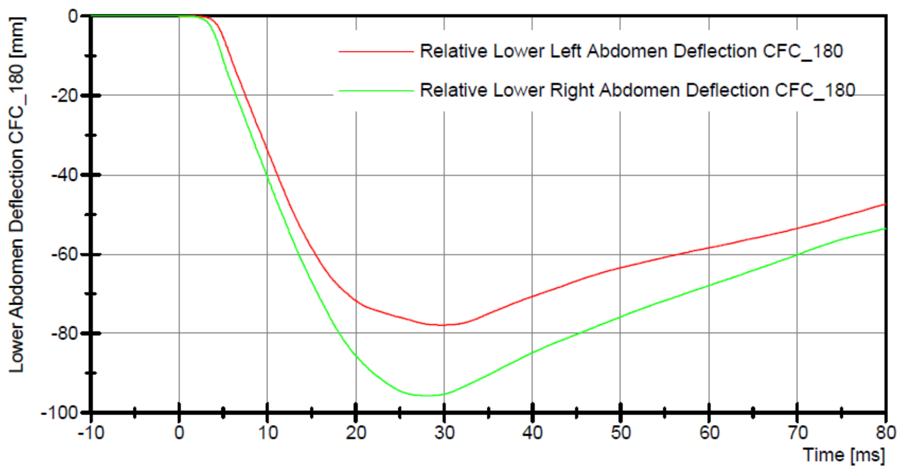

Figure 32. Asymmetry of lower abdomen deflection measurements (test 4-2A)

In this test program, the cable of the left string potentiometer started to fray during the first six tests. No spare was available, so testing continued. When the string potentiometer was removed from the dummy at the completion of the test program it was found that the retraction was no longer smooth. On disassembly of the string potentiometer no elements of the fraying cable were found in the internal mechanism, but it is possible that the frayed ends of the string were partially jamming the cable guide at the exit of the string potentiometer housing.

4.3 Impact Location and Impactor Thickness

The test program found that the deflection and VC at any single lower thorax and abdomen sensor was quite sensitive to the alignment of the impact with the sensor, with the measured deflection reducing with increasing offset from the sensor location. However, the abdomen and lower thorax region has deflection sensors at three vertical levels, and it was found that the deflection is picked up well by adjacent sensors. When normalized by the performance requirement, the VC was extremely consistent across the abdomen and lower thorax. In general, VC was more sensitive to variations in impact conditions than deflection.

4.4 Impactor Velocity

The upper abdomen showed the expected sensitivity to impactor velocity, with the deflection and VC both increasing with increasing impactor velocity. However, the lower abdomen did not show a consistent correlation between impactor velocity and deflection or VC. It is likely that this is because the tests were run with a 50 mm diameter impactor, which could interact with the top of the iliac wing of the pelvis – and this interaction could be quite different for slightly different impactor heights. It is TRL's intention to re-run these tests with a 25 mm diameter impactor to check the velocity sensitivity.

4.5 Other Issues

Chest deflection is defined in APTA (2013) as the maximum X-axis deflection measured at the sternum, presumably because the criterion is derived from 49 CFR 571.208; this regulation uses the Hybrid III ATD, which has a single chest deflection measurement point at the sternum. However, APTA (2013) defines that the workstation table tests should be conducted with either the THOR or H3-RS ATDs, which both have four points of chest deflection measurement. This allows better characterization of localized loading to the thorax, particularly to the lower thorax, than is possible with the single point of chest compression measurement in the Hybrid III. However, there is no formal agreement regarding how the sternum deflection should be predicted from the four individual measurements. Traditionally, taking the mean deflection from the top two thorax measurement points has been the means of estimating sternum deflection for the THOR.

For the purposes of this study, we have examined both the mean deflection at each level in the abdomen (e.g. upper abdomen), which is particularly relevant to the certification requirements and biofidelity targets for the dummy, as well as the individual left and right measurements at each level, which are relevant to the assessment of injury risk in workstation table tests. The use of the mean upper thorax or abdomen DGSP measurements is not defined in the THOR biofidelity manual, but is specified in the certification manual.

The maximum deflection at any sensor is the most relevant to the assessment of injury risk, because the loading from workstation tables may not be symmetrical and injury may be to only one side; in this case the mean value would underestimate the injury risk from the asymmetrical loading.

Table 11 shows the performance limits for the thorax and abdomen injury criteria defined in APTA PR-CS-S-018-13 (APTA, 2013). In all tests except one, at least one of these performance limits was exceeded – and in the remaining test the upper abdomen deflection was only 1.16 mm below the limit. This test series therefore has evaluated the performance of the abdomen beyond the range required to pass or fail the APTA standard.

Table 11. Chest and abdomen performance limits in APTA PR-CS-S-018-13

Body Region	Deflection Limit (mm)	VC Limit (m/s)
Thorax	63	1.0
Upper abdomen	67	1.98
Lower abdomen	67	1.98

5. Conclusion

The performance of the abdomen of the H3-RS ATD was assessed in a series of tests based on the standard abdomen biofidelity tests for frontal impact crash test dummies. The H3-RS abdomen is of particular importance for assessing the safety of workstation tables in passenger trains and providing indication to table manufacturers on how to improve the safety of their designs. The study examined the biofidelity of the standard H3-RS abdomen and two alternatives that TRL developed to improve the performance with some table designs. Following the biofidelity tests, bag design B was chosen and the repeatability and sensitivity to impact location, impactor size and impactor velocity were assessed.

Biofidelity and Abdomen Design

- The results of the biofidelity tests showed little difference between the three bag designs. Bag design B was selected for the remainder of the test program on the basis that it was considered most likely to prevent narrow table edges from penetrating between the abdomen and the rib structures and therefore, potentially bypassing some of the chest and abdomen deflection instrumentation. This should ensure the most consistent assessment of the safety of table edge designs regardless of the vertical position of the table relative to the seat base.
- The biofidelity of the upper abdomen for all three abdomen designs was very good, and better than the THOR-NT.
- The biofidelity of the lower abdomen for all three abdomen designs was good and can probably be fine-tuned to be as good as the THOR-NT.

Repeatability (tests conducted on abdomen bag B only)

- Where symmetrical loading was applied, a good level of repeatability was shown in the upper abdomen deflection measurements.
- The lower abdomen deflection showed good repeatability, and was sensitive to the location of impact with the narrow impactor used in these tests. However, although the loading was symmetrical, the left and right string potentiometer outputs were asymmetrical, possibly due to fraying of the cable on one of the string potentiometers.

Sensitivity (tests conducted on abdomen bag B only)

- The H3-RS was sensitive to impact location. Maximum deflections were recorded when the impact point coincided with the sensor locations. However, as the impact location moved away from one sensor, it was picked up by an adjacent sensor such that severe loading was always picked up by either the lower or upper abdomen or by the lower thorax. The VC measurements, normalized by the performance thresholds, showed a consistent assessment of the impact severity across a range of impact locations.

- The H3-RS showed sensitivity to velocity at the upper thorax, with increasing transducer outputs as input severity increased.
- However, this was not demonstrated at the lower abdomen, possibly due to interactions with the pelvis of the H3-RS. TRL will perform additional tests to check this, by using a narrower impactor to ensure there is no interaction with the pelvis.

Recommendations

- Further evaluate the performance of the lower abdomen string potentiometers and, if necessary, specify a more robust alternative transducer or cable guide to minimize fraying of the string potentiometer cables.
- Consider including a limit on the asymmetry of the deflection measurements in certification tests to better detect potential damage to the sensors.

6. References

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5. Nusholtz, G., Kaiker, P. (1994 May 23-26). “Abdominal Response to Steering Wheel Loading,” 14th International Technical Conference on the Enhanced Safety of Vehicles (ESV). Paper no. 94-S1-O-05. US Department of Transportation, NHTSA.
6. Cavanaugh, J., Nyquist, G., Goldberg, S., King, A. (1986 October 27-29). “Lower Abdominal Tolerance and Response,” 30th Stapp Car Crash Conference, Paper no. 861878.

Appendix A.
Aggregated Test Matrix

Table A.1. Aggregated test matrix

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#1	1-1A	A	At DGSP +15 mm	26.7 mm SW‡	18	8.0	576
#2	1-2A	A	At string pot	25 mm bar	32	6.1	595
#3	1-2B	B	At string pot	25 mm bar	32	6.1	595
#4	1-1B	B	At DGSP +15 mm	26.7 mm SW‡	18	8.0	576
#5	1-1C	C	At DGSP +15 mm	26.7 mm SW‡	18	8.0	576
#6	1-2C	C	At string pot	25 mm bar	32	6.1	595
#7	4-2A	B	At string pot	25 mm bar	32	6.1	595
#8	4-2B	B	At string pot	25 mm bar	32	6.1	595
#9	4-1A	B	At DGSP +15 mm	26.7 mm SW	18	8.0	576
#10	4-1B	B	At DGSP +15 mm	26.7 mm SW	18	8.0	576
#11	2-1A	B	At DGSP +15 mm	25.4 mm bar	18	8.0	576
#12	2-1B	B	At DGSP +40 mm	25.4 mm bar	18	8.0	576
#13	2-1C	B	At DGSP -10 mm	25.4 mm bar	18	8.0	576
#14	2-2B	B	String pot +25 mm	25 mm bar	32	6.1	595
#15	2-1D	B	At DGSP	25.4 mm bar	18	8.0	576
#16	3-1D	B	At DGSP	50 mm bar	18	8.0	576
#17a	3-1A	B	At DGSP +15 mm	50 mm bar	18	8.0	576
#18	3-1B	B	At DGSP +40 mm	50 mm bar	18	8.0	576
#19	2-1E	B	At DGSP -35 mm	25.4 mm bar	18	8.0	576
#20	2-1E	B	At DGSP -35 mm	25.4 mm bar	18	8.0	576
#21	3-1C	B	At DGSP -10 mm	50 mm bar	18	8.0	576
#22	3-2A	B	At string pot	50.8 mm bar	32	6.1	595

Test Order	Test No.	Abdomen Bag Design	Vertical Impact Location	Impactor Shape and Diameter (mm)	Impactor Mass (kg)	Impact Velocity ($m \cdot s^{-1}$)	Kinetic Energy (J)
#23	3-2B	B	String pot +25 mm	50.8 mm bar	32	6.1	595
#24	5-1A	B	At DGSP +15 mm	50 mm bar	18	8.0	576
#25	5-1B	B	At DGSP +15 mm	50 mm bar	18	8.0	576
#26	5-2A	B	At string pot	50.8 mm bar	32	6.1	595
#27	5-2B	B	At string pot	50.8 mm bar	32	6.1	595

‡ Steering Wheel representation

Appendix B.
Impactor Drawings

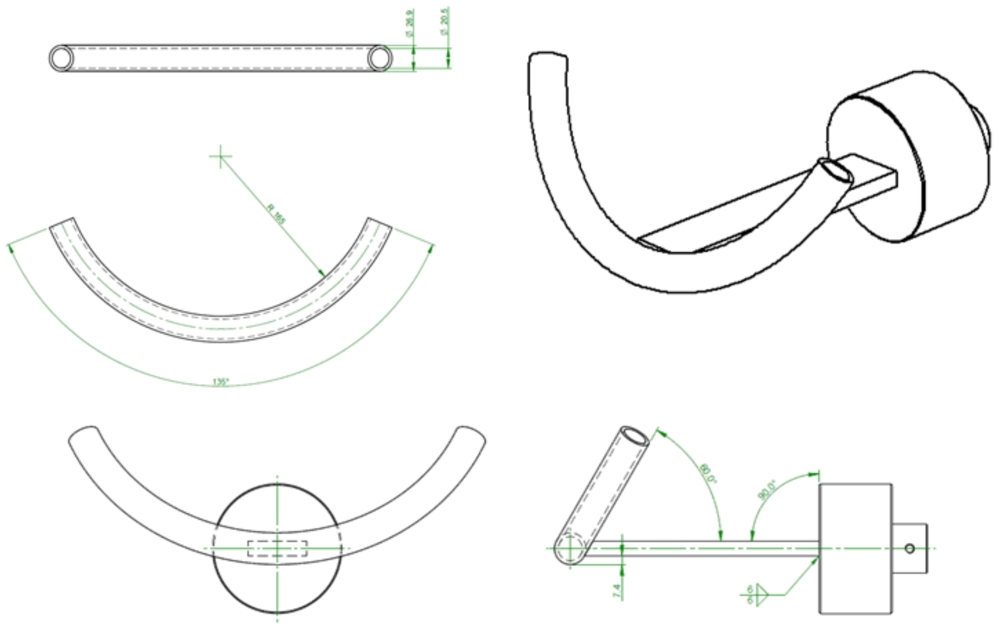

Figure B.1. Engineering drawing of steering wheel impactor

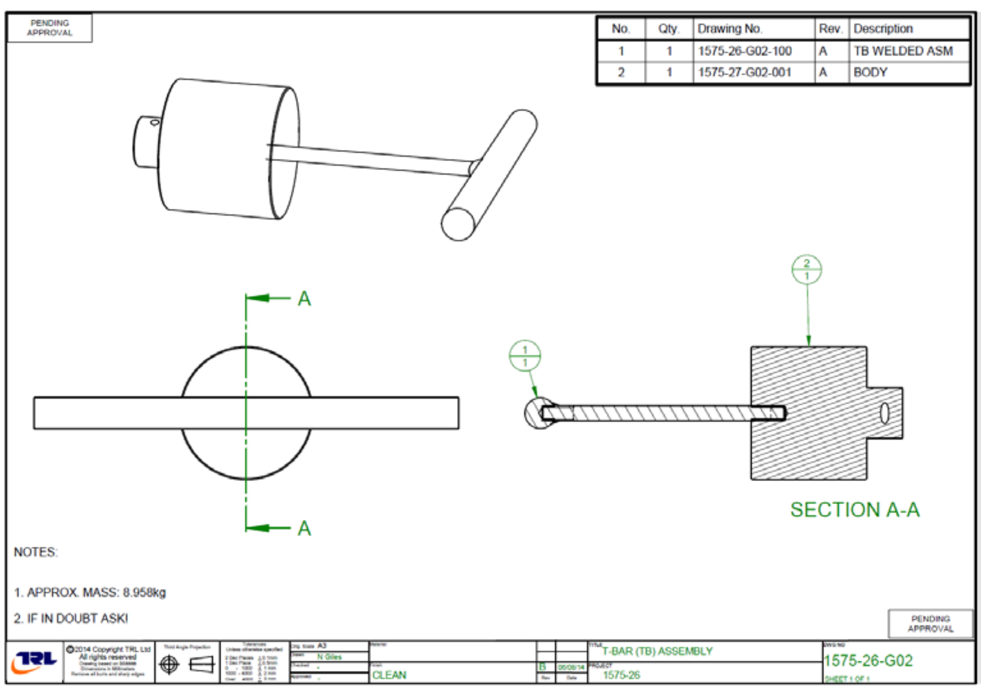

Figure B.2. Engineering drawing of 25 mm diameter, 32 kg bar impactor

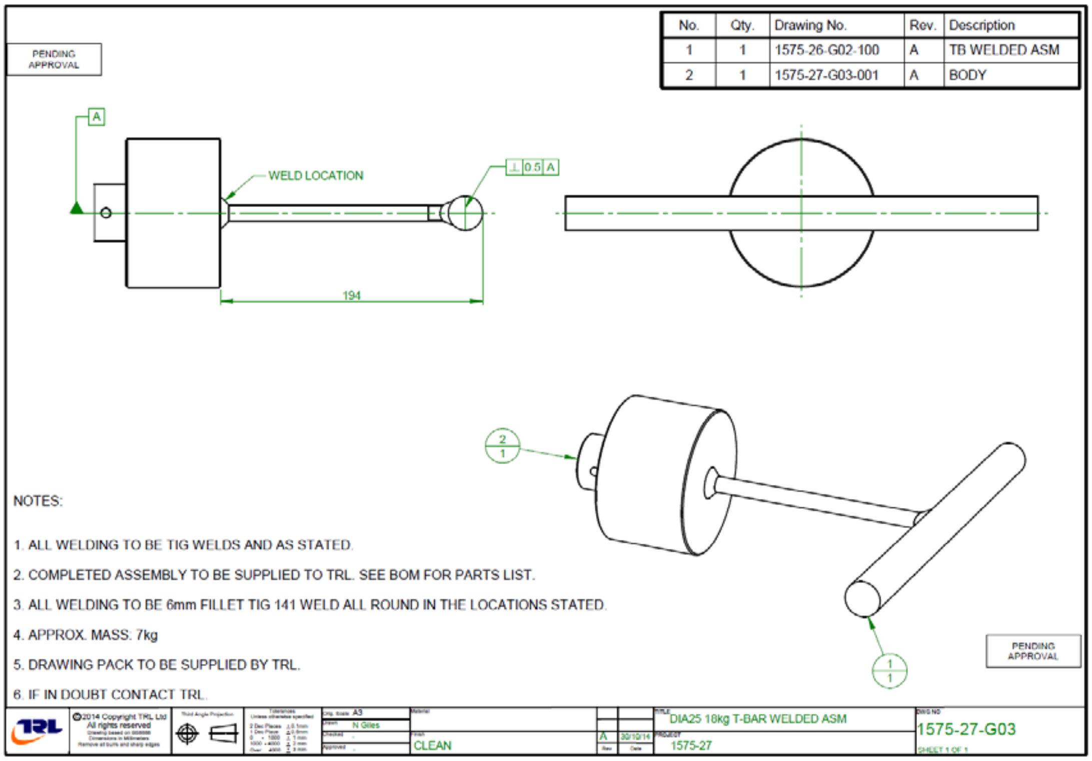

Figure B.3. Engineering drawing of 25.4 mm diameter, 18 kg bar impactor

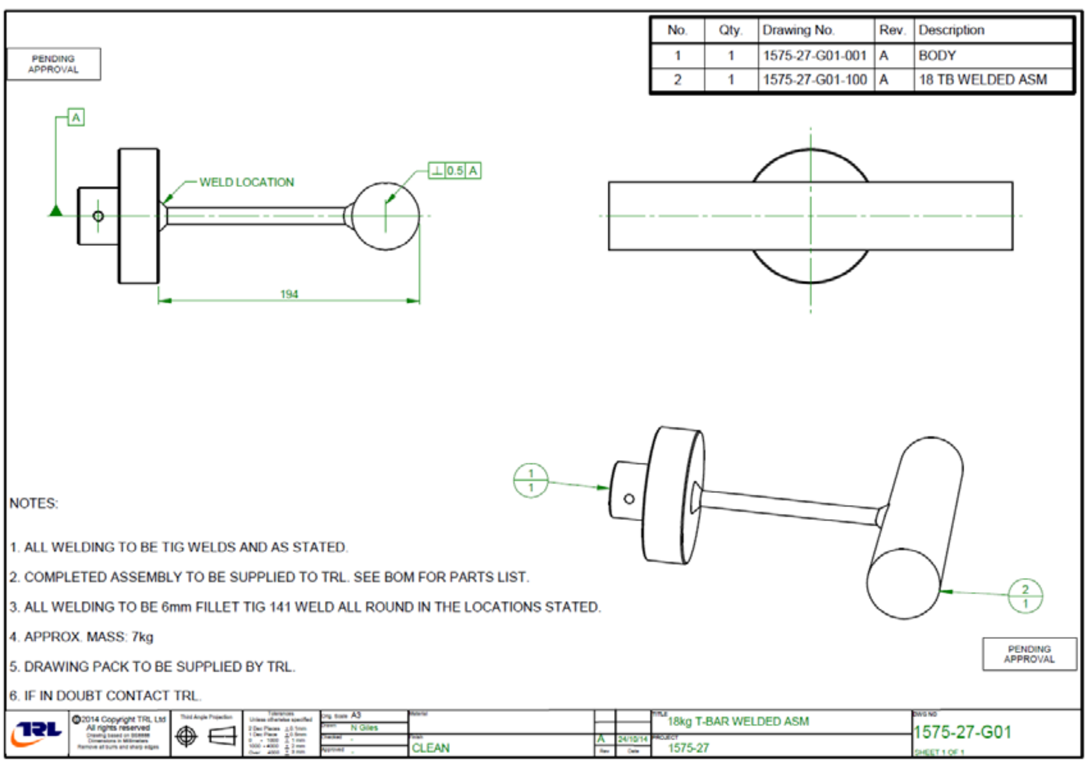

Figure B.4. Engineering drawing of 50 mm diameter, 18 kg bar impactor

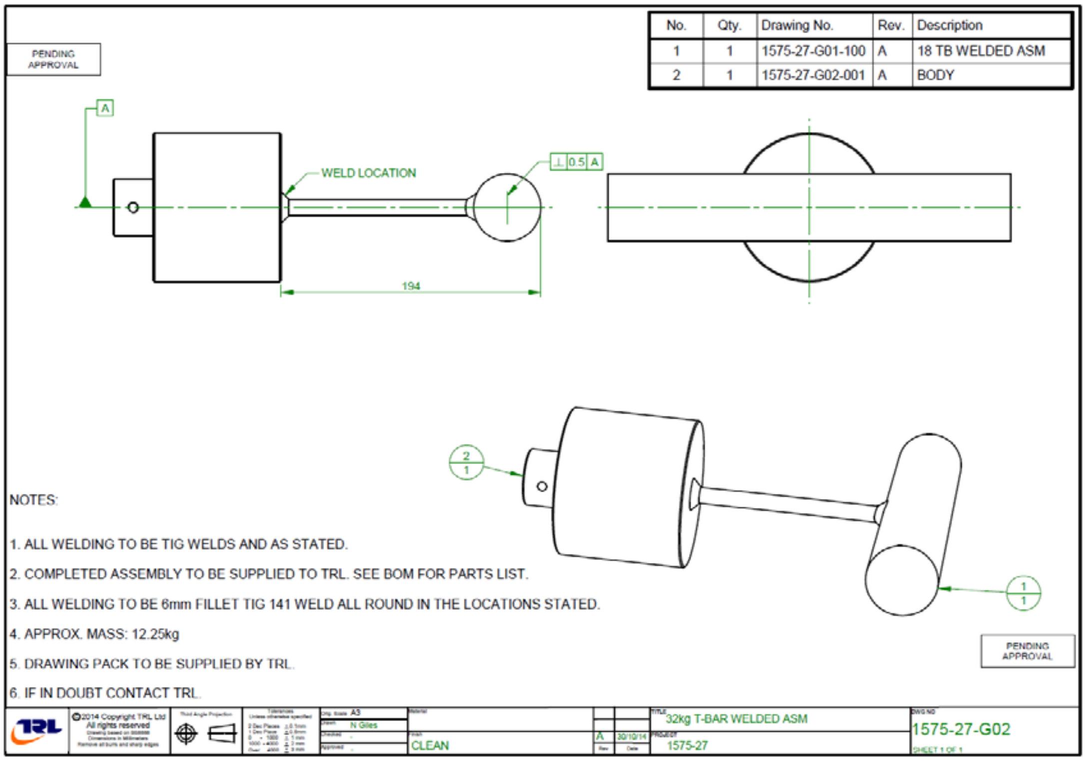

Figure B.5. Engineering drawing of 50.8 mm diameter, 32 kg bar impactor

Abbreviations and Acronyms

APTA	American Public Transportation Association
ATD	Anthropomorphic Test Device
CFR	Code of Federal Regulations
DGSP	Double-Gimballed String Potentiometer
g	Acceleration due to gravity ($9.80665\ m\cdot s^{-2}$)
NHTSA	National Highway Traffic Safety Administration
PMHS	Post Mortem Human Surrogates
Pot	Potentiometer
SAE	Society of Automotive Engineers
THOR	Test device for Human Occupant Restraint (an advanced car crash test ATD for use in frontal impacts)
VC	Viscous Criterion ($m\cdot s^{-1}$)