EUROPEAN ENHANCED VEHICLE-SAFETY COMMITTEE

Working Group 12 Report, Document N°252

Status of Side Impact Dummy Developments : WorldSID Development

January 2004

EEVC WG12 Report, Document No. 252

Status of Side Impact Dummy Developments: WorldSID Development

EEVC WG12 Report to the EEVC Steering Committee

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by

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on behalf of European Enhanced Vehicle-safety Committee (EEVC) Working Group 12

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1 Introduction

Harmonisation of standards, the appearance of more advanced occupant restraint systems and higher levels of occupant protection required in side impact have been the main drivers for intensified research and development work in this area of vehicle safety. In May 2000, EEVC WG12 issued Document 101 ‘Status of Side Impact Dummy Developments in Europe’ detailing the modifications to the EUROSID-1 dummy that were incorporated in the ES-2 dummy. The modifications were made in particular to improve the acceptability of the dummy as an interim world-wide harmonised side impact dummy until the moment that a ‘next generation’ side impact dummy would become available. In December 2003, WP29 ratified the decision by GRSP to start the use of the ES-2 dummy in ECE R95 in apparent anticipation of a similar step being taken in FMVSS 214 soon.

In the meantime, the development of a world-wide acceptable, ‘next generation’ side impact dummy has progressed significantly. The development of the WorldSID 50th percentile male dummy was initiated in 1997 as part of a drive by ISO to establish globally harmonised side impact regulations and to improve the assessment of the safety of vehicles in a side impact. In particular, new restraint systems such as side airbags and increasing protection requirements require an improved dummy with appropriately tailored measurement capabilities. The International Harmonised Research Activities (IHRA) Working Group on Side Impact, that is currently developing a new set of harmonised regulatory test procedures for side impact, recommends the use of WorldSID 50th percentile male and 5th female dummies when available. This makes WorldSID the best candidate for application in a future potential Global Technical Regulation on Side Impact.

Following previous updates on side impact dummy developments by WG12, this document outlines the development of the WorldSID dummy and the results of the extensive testing programmes that the dummy has undergone in Europe and elsewhere. The objective is to update the reader about the status of the WorldSID dummy development and to present an objective view about its performance to date from the European perspective.

2 WorldSID Development

2.1 Introduction

The predominant cause of fatal and other serious injuries in European road accidents is side impact. This type of impact currently accounts for one third of accidents and for half of the fatalities recorded. Up until the present time, for side impact testing, several different dummies have been used, both for regulatory testing and for research and development, around the world. The world-wide adoption of a single adult, 50th percentile male side impact dummy would be advantageous for several reasons. Firstly, it would contribute to the process of global harmonisation of regulatory test procedures, which is the objective of the International Harmonised Research Activities (IHRA) group. The need to develop cars and restraint systems using different dummies for different markets would also be eliminated. This would potentially reduce vehicle and restraint system development costs and allow development efforts to be channelled more effectively towards meeting a single set of objectives. The use of a single dummy by regulatory bodies and by consumer organisations would help to ensure that published results are consistent and unambiguous, resulting in the public being better informed. Furthermore, the availability of an improved dummy with better measurement capabilities would also help to gather more data and increase knowledge relevant to the protection of occupants. A single dummy would drive vehicle design in a single direction, but could lead to increased optimisation of vehicles to the dummy.

It is in this context that in November 1997 work began on the development of an entirely new, advanced side impact crash test dummy - the 50th percentile male WorldSID (World-wide Side Impact Dummy). The development of this dummy has been overseen by an international group of experts, the WorldSID Task Group, working under the auspices of the International Organisation for Standardisation (ISO) Working Group on anthropomorphic test devices (ISO/TC22/SC12/WG5). The Task Group entrusted the actual development work to a Design Team consisting of established dummy and instrumentation manufacturers and research organisations. The development of the WorldSID dummy has been supported, either financially or through participation in the activities of the group, by governmental, industrial and research organisations from around the world. Part of the European contribution has been through the participation of the SID-2000 project under the European Commission Framework Programme IV and, subsequently, the SIBER project under Programme V. During the development of the first prototype, the SID-2000 Consortium was responsible for design of the head, neck and pelvis, and jointly responsible for the shoulder, thorax and abdomen complex. In order to perform these tasks, representatives of the SID-2000 Consortium took part in the work of the Design Team, each participating organisation being responsible for the development of specific parts of the dummy.

The WorldSID dummy has been developed with the goal of meeting the dynamic response requirements laid out in the document ISO TR9790 [ISO, 1997], which are similar but not exactly identical to the EEVC requirements. The target performance that was specified was a rating of ‘good’ to ‘excellent’, on the scale described in the TR 9790 report, for all segments of the dummy and for the dummy overall. As far as is possible, the dummy was also intended to meet the newer IHRA biofidelity requirements, although these requirements were not published until the pre-production version had already been designed. The development of the dummy has been in four stages: specification, prototype dummy, prototype revision 1 and pre-production dummy. Each of these stages is covered in the following sections.

2.2 WorldSID Specification

The WorldSID Task Group (TG) reviewed the performance of the existing side impact dummies (DOT SID, EUROSID-1 and BioSID) to determine which features met the requirements of the various dummy users world-wide (Regulators, consumer groups, manufacturers and researchers) and what improvements were needed. From this review, a specification for a future advanced side impact dummy was developed. This consisted of general requirements and specifications for particular body regions [TG N60r2, 1999]. The general requirements included:

- Symmetrical design (i.e. capable of left or right hand side impacts, or both to enable the study of occupant interaction in side impacts);
- Should produce reasonable data for impacts at ±30° in the horizontal plane and ±10° in the vertical plane;
- On-board data acquisition system (DAS);
- Metric design;
- Mid-sized (50th percentile) male to the latest IHRA anthropometry, with an in-vehicle seated posture;
- ISO biofidelity rating of good to excellent (≥6.5 out of 10);
- Durable (minimum of 10% above injury criteria);
- Reproducible (CV_{max} = ±10% on injury assessment and calibration channels);
- Repeatable (CV_{max} = ±7% on injury assessment and calibration channels).

2.3 Description of the WorldSID Prototype Dummy

2.3.1 Introduction

The design of the WorldSID prototype dummy is described in the following sections, followed by a summary of the evaluation of the dummy.

2.3.2 General

The WorldSID dummy is designed to meet the anthropometry of a mid size male defined in the AMVO study of UMTRI [Schneider et al., 1983]. A correction to the original date set was made in the position of the H-point (x+2, z+10.4). [Moss et al. 2000].

Figure 1: The WorldSID prototype dummy

2.3.3 Head

The head was developed by the SID-2000 Consortium to provide better performance than existing dummy heads when interacting with airbags and padded or rigid structures. Reference for the anthropometry was taken from the UMTRI data set. The head is made of a polyurethane skull moulded directly into a PVC skin and split lines and other facial features (eyes, nose, lips) are absent (Figure 2). The internal cavity for instrumentation contains a core block that houses all of the instrumentation for accurate alignment and ease of handling (Figure 3). The core block includes the upper neck load cell that acts as the head-neck interface. The head skin features three small indents on each side of the head, marking the head centre of gravity (CG) and occipital condyle (OC) projection and a marker for indicating the head horizontal orientation.

Figure 2: WorldSID head and instrumentation core

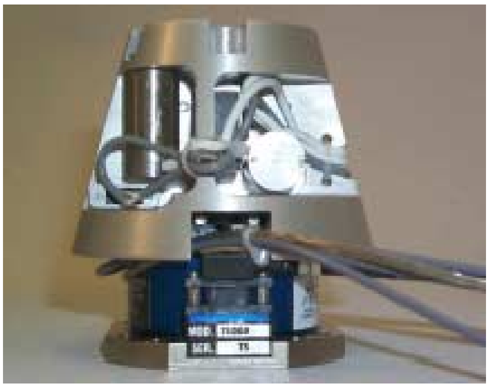

Figure 3: Detail of head instrumentation core

2.3.4 Neck

Development of the WorldSID neck was undertaken by the SID-2000 Consortium. The neck represents the human neck as it attaches to the head at the occipital condyles-atlas joint and to the torso at the C7-T1 junction. It has a similar mass, and mass distribution to that of the human as available from the reference UMTRI data set. The design (Figure 4) is based on the EUROSID-1 neck, with improved attachment, improved pre-impact position stability, and elimination of buffer dislocation. A lower neck bracket allows neck angle adjustment from 9° rearward to 27° forward. The neck optionally incorporates a shroud to provide proper anthropometry and prevent unrealistic loading from airbag interaction. A universal spine load cell and a T1 tri-axial accelerometer are incorporated at the base of the neck. In order to achieve both frontal and lateral biofidelity targets a new neck buffer design has been used (Figure 5).

Figure 4: WorldSID neck

Figure 5: Detail of WorldSID neck buffers

2.3.5 *Shoulder-Thorax-Abdomen*

Development of the shoulder-thorax-abdomen has been by First Technology Safety Systems (FTSS) and the SID-2000 Consortium. The segment consists of one shoulder, three thorax and two abdomen rib modules (Figure 6), which are constructed of a super elastic alloy that will accommodate 75 mm of lateral deflection. Each rib consists of an inner and outer band (see Figure 7). The inner band is connected to the spine box and has a damping material bonded to its inner surface. The outer rib is connected to the spine box at the rear and a flexible sternum element at the front. The ribs are in a horizontal position in the seated posture, except for the shoulder rib and the top thoracic rib. The ribs contain deflection sensors (IR-TRACC's – see Figure 7). The rib modules are mounted to a rigid spine box that contains some of the on-board DAS modules. The anthropometry is based on the UMTRI data set and is complimented with recent data from the ASPECT program. The shoulder, thorax and abdomen areas are symmetrical about the mid-sagittal plane and may be instrumented for left- or right-hand impacts.

2.3.6 *Lumbar Spine*

The WorldSID lumbar spine represents the T12 to L5 vertebrae and is used to de-couple the upper and lower parts of the dummy (Figure 8). The lumbar spine allows up to 50 mm of lateral shear between the upper spine and the pelvis.

Figure 6: Shoulder-thorax-abdomen assembly

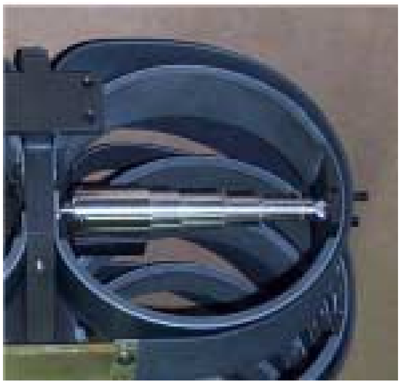

Figure 7: Outer and inner shoulder rib with IR-TRACC displacement transducer

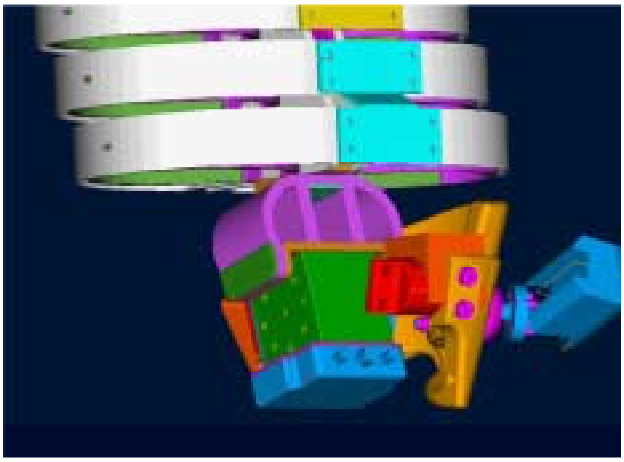

Figure 8: Lumbar spine (in purple), also showing the abdomen ribs and part of the pelvis assembly

2.3.7 Arm

2.3.7.1 Full Arm

The WorldSID full arm has been developed by RA Denton. The design of the full arm is based on the SAE airbag interaction arm and the anthropometry is based on the UMTRI anthropometry data set. It is constructed of a metallic instrumented bone structure with a soft flesh and skin covering (Figure 9). The flesh is removable for access to the instrumentation. The load cells are integral parts of the bone structure at the upper arm, lower arm and elbow, and structural replacements for these will be provided if the load cells are not used. Other instrumentation includes tri-axial linear accelerometers at the elbow and wrist, and an elbow rotation sensor. There is a gripping hand and the arm has a 3-degree of freedom shoulder joint, 1-degree of freedom elbow joint, and 1-degree of freedom wrist joint. The shoulder joint incorporates a three axis load cell capable of measuring shoulder forces.

2.3.7.2 Half Arm

The half arm has been developed by First Technology Safety Systems. The half arm represents only the upper arm of the midsize male, from the gleno-humeral joint to the elbow. It is intended for testing where a full articulated arm is not required and could cause test repeatability problems. This arm has a deformable flesh over a metal skeletal structure. The deformable flesh is fabricated from a thin vinyl skin over urethane foam. The flesh contour is derived from the EUROSID-1 half arm. The half arm is intended for use in full-scale vehicle-to-pole and vehicle-to-vehicle crash tests. The three channel shoulder load cell is interfaced to the shoulder rib.

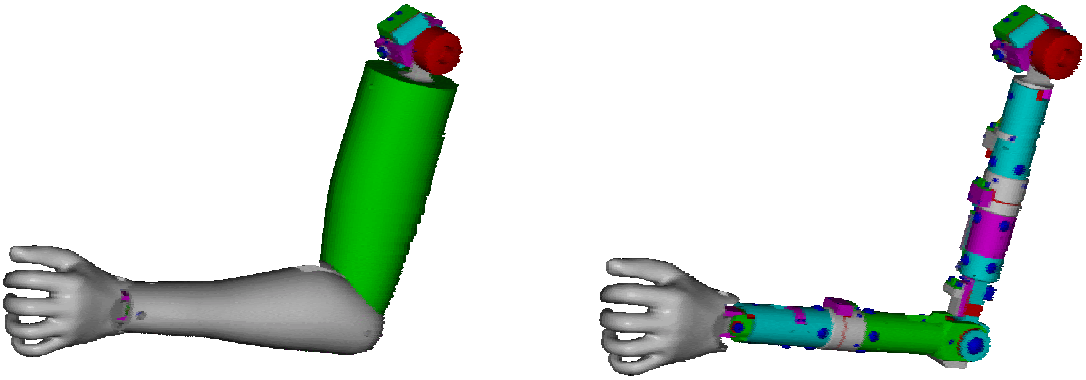

Figure 9: Full arm assembly (including shoulder load cell) with and without flesh

2.3.8 Pelvis

The pelvis was developed by the SID-2000 Consortium. The pelvis is a semi-rigid structure that closely resembles the human anthropometry (see Figure 10), both in terms of the external flesh (based on the UMTRI data set) and the internal bony structure (based on the Reynolds study). It is designed to allow a human-like range of motion, pressure mapping to the seat, correct lateral force-deflection response and mass distribution. The pelvis has internal load cells at the pubis and the sacrum and is designed to have no uninstrumented load paths. In addition, a lower lumbar spine load cell and in-dummy DAS unit are integrated with the sacrum load cells.

Figure 10: Pelvis assembly with and without flesh

2.3.9 *Upper Leg*

RA Denton has developed the WorldSID upper leg, which incorporates a rigid instrumented bone structure with a soft flesh and skin covering (Figure 11). It extends from the pelvis interface to the knee-lower leg interface. The knees are designed as part of the upper leg and have medial and lateral uniaxial force sensing. Load cells are integral parts of the bone structure in the femoral neck and upper and lower thigh positions and structural replacements will be provided. The femur bones feature a greater trochanter representation according to the UMTRI position. The bone structure is used as a mounting for DAS modules at the mid-thigh position. A two-piece flesh extends from the pelvis to cover the knee and provides a near continuous outer surface with the pelvis flesh. This flesh has cable routings built in and is split to allow easy removal from the bone structure. In a compressed (seated) condition, the flesh shape simulates the shape defined by the UMTRI shell.

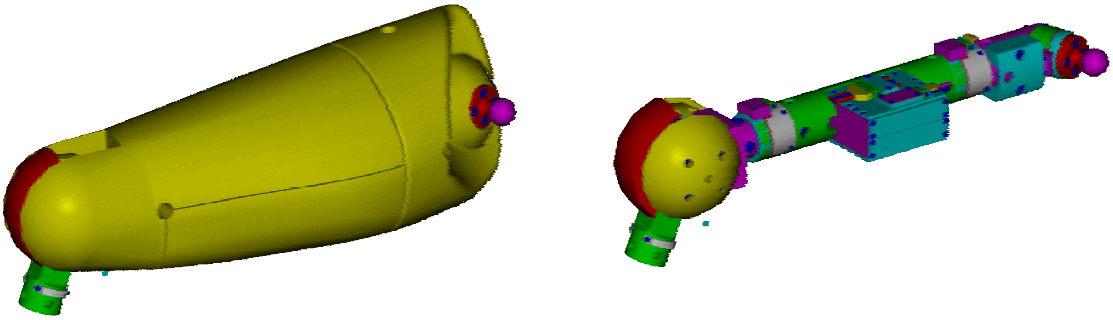

Figure 11: Upper leg assembly with and without flesh

2.3.10 *Lower Leg*

Applied Safety Technologies Corporation (ASTC, now Denton ATD) have developed the WorldSID lower leg. The lower leg skeleton consists of a rigid bone structure and is designed to represent the mid-sized male as represented by the UMTRI data set. The skeletal structure is represented by an instrumented metallic structure, which includes a lower leg bone, ankle joint and foot with shoe. It contains integrated upper and lower tibia load cells, ankle rotation sensors and integrated cable routing. The ankle has three-degrees of freedom with soft joint stops to provide human like inversion, eversion and dorsiflexion. There is also an integrated foot-shoe moulding. Skin and flesh are represented by a polyurethane moulded part, covering the bone structure.

2.3.11 In-dummy Data Acquisition System

Development of the in-dummy data acquisition system (TDAS ATD) was undertaken by Diversified Technical Systems. The data acquisition system is wholly contained within the WorldSID which eliminates most of the umbilical wires normally required to transmit the sensor signals from inside the dummy to a data acquisition system located on, or off the vehicle. With over 200 possible data channels a traditional umbilical system would not be practical due to cable mass and handling issues. The in-dummy DAS also reduces the time required for WorldSID installation and checkout. A small number of umbilical cables are still required for power (including power to the instrumentation), communications and triggering.

The TDAS ATD system combines sensor signal conditioning, analogue to digital circuits, microprocessor, memory and communication circuits into the same package. This system moves a significant portion of the signal conditioning to the sensor along with self-calibration and sensor ID capabilities. This system breaks the traditional data acquisition system into two main parts; sensor modules and DAS modules. Each dummy contains seven DAS modules: two in each upper leg, one in the pelvis and two in the spine box.

2.3.12 Instrumentation

2.3.12.1 Accelerometers and Tilt Sensors

The development of linear acceleration, angular acceleration, and tilt sensors was undertaken by Endevco. The WorldSID is equipped with newly designed linear tri-axial accelerometers that are positioned at 15 locations throughout the dummy (considering the struck side only). The tri-axial accelerometer footprint is almost the same as a conventional uni-axial accelerometer footprint. The WorldSID is also equipped with six tilt sensors, two in the head, torso and pelvis, measuring the orientation of these parts prior to impact to assist with set-up of the dummy. The uni-axial angular accelerometer that will be used in this dummy is based on Endevco's angular accelerometer type 7302B. Three of these units are positioned in the head on the x, y, and z axes and two in the thorax aligned with the horizontal axes of the thorax.

2.3.12.2 Load Cells

Development of the load cells has been sub-contracted to RA Denton. Design of the load cells was primarily driven by the number and type of channels, capacity for each of the channels, and the body part design, into which they are incorporated. The design intent was to minimise the number of types of loads cells in the WorldSID by using universal-types where possible. The full instrumentation map is shown in Figure 12

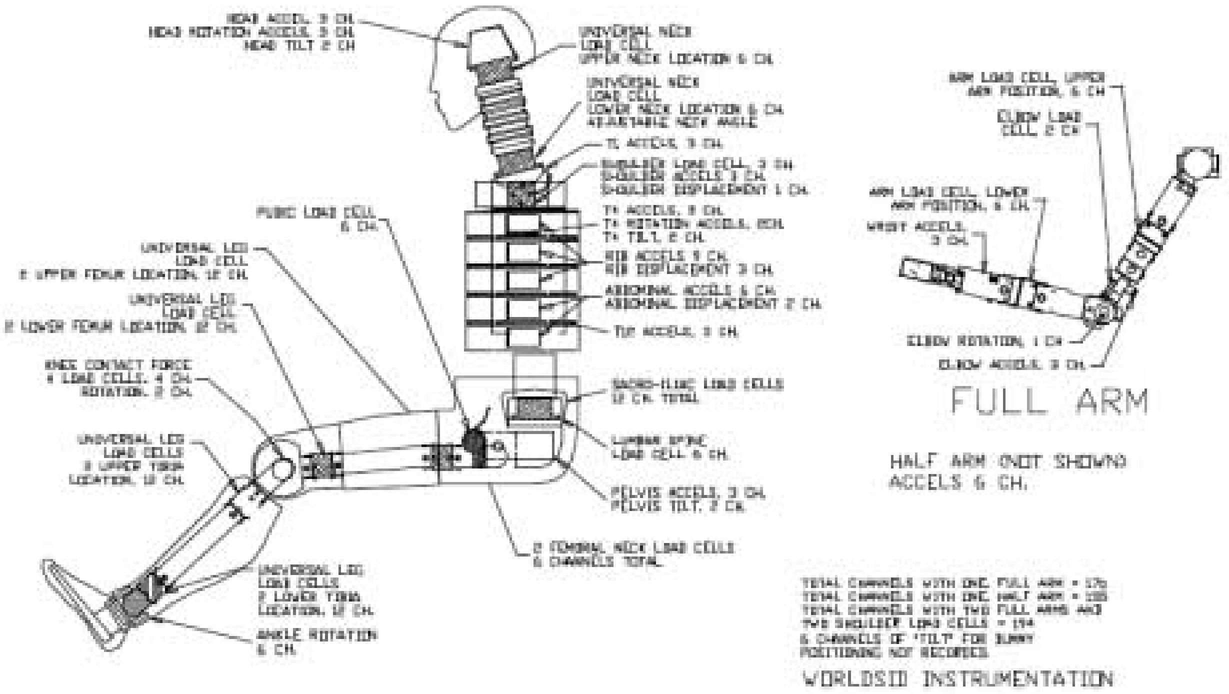

Figure 12: WorldSID prototype instrumentation map

2.3.13 Summary of WorldSID Prototype Evaluation

The WorldSID prototype dummy was evaluated to the ISO TR9790 [ISO, 1997] dynamic response requirements. These targets were derived from PMHS and volunteer responses in lateral impact pendulum, sled and drop tests. These requirements sometimes differ from the EEVC requirements, even when both are based on the same PMHS or volunteer work. In some cases different subsets of the available data have been chosen by the two groups, either eliminating different outliers or removing different tests because of problems with the performance of the test or the data.

2.3.13.1 ISO Biofidelity Rating

The ISO biofidelity rating for the WorldSID prototype is given in Table 1. This was lower than the target biofidelity rating of good (>6.5 to 8.6) or excellent (>8.6 to 10). The first column refers to the biofidelity rating published in Cesari et al. [2001]. Later, it was discovered that a mistake was made in the calculation of the head response and that the actual score for head biofidelity of the WorldSID prototype was 5. Clearly this influences the overall score which dropped to 5.4 overall as shown in the second column of Table 1.

Body region	ISO biofidelity rating published	ISO biofidelity rating corrected
Head	10	**5**
Neck	3.6	**3.6**
Shoulder	5.2	**5.2**
Thorax	6.9	**6.9**
Abdomen	6.3	**6.3**
Pelvis	4.2	**4.2**
Overall	6.2	**5.4**

Table 1: ISO TR9790 biofidelity rating for the WorldSID prototype dummy

2.4 Description of the WorldSID Revision 1 Prototype Dummy

2.4.1 Introduction

In order to improve the ISO biofidelity rating of the WorldSID dummy, a number of modifications were made to the prototype design and a revised WorldSID prototype dummy was produced and evaluated. The revised dummy is referred to as WorldSID Revision 1 Prototype. The modifications to the dummy are listed below, followed by the revised ISO biofidelity rating (see Table 2).

2.4.2 Neck

The biofidelity rating of the original neck was found to be very low (3.6 out of 10). However, the ISO neck tests are sled tests and it was speculated that the low biofidelity rating was due to the shoulder being too soft (i.e. the input to the neck being incorrect, not the neck itself). Therefore, no changes were made to the neck design.

2.4.3 Shoulder

The original shoulder design exhibited large compression response when the pendulum impactor acceleration met or slightly exceeded the corridor. This meant that the shoulder rib compression had to be reduced without increasing the force. To achieve this, the thickness of the damping material on the inner shoulder rib was increased from 4 mm to 9 mm and the stiffness of the shoulder plug was changed to reduce the impact force. In addition, damage to the shoulder IR-TRACC had occurred in one of the early sled tests due to over compression of the shoulder rib. A rib stop was introduced to limit the compression of the shoulder rib to protect the rib and the IR-TRACC.

2.4.4 Half Arm

The half arm was changed in the revision 1 upgrade to meet the UMTRI shell surface model.

2.4.5 Pelvis and Legs

It was found in the initial biofidelity tests that the pelvis was too stiff. In sled tests, it was found that there was too much contribution to the measured pelvis response from the thigh mass and, in pendulum impacts, that the left and right parts of the pelvis were too rigidly coupled. A number of approaches were taken to correct these problems:

- The pelvic bone material was softened;
- A mock-up pubic symphysis load cell was reduced in size and fitted between soft polyurethane buffers with bonded-on end plates.
- The ratio of bone to flesh mass in the upper leg was changed to give a more biofidelic mass distribution. The femur bone was lightened by changing the material from steel to aluminium, by removing one of the two six-axis load cells and by removing material from some parts. The DAS module housing was also removed and the DAS re-located to the femur flesh from the femur bone. At the same time, the flesh mass was increased by changing from vinyl covered foam to solid vinyl.

2.4.6 ISO Biofidelity Rating of the Modified Prototype WorldSID

The ISO biofidelity rating of the modified WorldSID revision 1 prototype dummy is shown in Table 2 [Hautmann et al, 2003]. It was felt by the WorldSID TG that it would be easy to tune the head to achieve a biofidelity rating of 10, so the rating for the modified dummy with a head rating of 10 is also given.

Hautmann et al. [2003] claimed that the thorax response improved because of rib softening due to extensive testing and a better balance in the dummy due to improvements in the shoulder and pelvis influencing the thorax response in the full body drop and sled tests. No separate explanations were given for the improved abdomen response with the revision 1 prototype. In Hautmann et al. [2003], a table is given showing the responses of different revisions.

Body region	**ISO biofidelity rating**	**ISO biofidelity rating (with modified head)**
Head	5	10
Neck	5.2	5.2
Shoulder	6.7	6.7
Thorax	7.7	7.7
Abdomen	6.6	6.6
Pelvis	7.3	7.3
Overall	6.5	7.3

Table 2: ISO TR9790 biofidelity rating for the modified WorldSID revision 1 prototype dummy

3 SIBER WorldSID Prototype Evaluation

3.1 Objective

The Prototype WorldSID dummy has been evaluated by the SIBER EC project as part of a wider programme to contribute to the reduction of injuries in side impact accidents. The SIBER project follows on from the earlier SID-2000 EC project and both projects have contributed to the development of parts of the WorldSID dummy. The objectives of the SIBER WorldSID Prototype test programme were:

1. To assess the sensitivity of the dummy to variations in test conditions, according to requirements given by the Task Group in document TG N60R2, and
2. To investigate the biofidelity of body parts.

In the sensitivity tests the WorldSID prototype sensitivity to various impact conditions, such as impact direction, position and impact velocity was investigated. The sensitivity of the dummy to belt pre-tensioning systems was also assessed.

In SIBER Work Package 2, the knowledge on side impact response of the human body was expanded through PMHS testing on the shoulder and lumbar spine. The PMHS tests were replicated on the WorldSID Prototype to compare the dummy responses to the newly obtained biomechanical data. At the request of the WorldSID Tri-chair, reruns of the Heidelberg sled biofidelity tests were conducted to assess the pelvis-thigh and shoulder-thorax biofidelity of an updated WorldSID Prototype (version February 2002).

3.2 Sensitivity to Crash Parameters

3.2.1 Whole Dummy Sensitivity Tests

The sensitivity to crash parameter tests were conducted on a side impact simulator on a HyGe acceleration sled facility (MSIS, MIRA). The dummy was seated in a simulated car interior, with current production car components, and subjected to impacts of an intruding door at realistic impact velocities. The velocity profiles of the door were derived from those measured in full-scale tests. The dummy seating position was changed to study changes in dummy response. The sensitivity of the dummy to seat-belt pretensioners was also assessed.

Comparison of WorldSID to EUROSID-1:

- WorldSID has similar overall kinematics to EUROSID-1.
- WorldSID thorax is not sensitive to the double peak velocity profile for which EUROSID-1 is sensitive.
- WorldSID pelvis has a lower stiffness producing delayed loading.

Effect of seat-belt pretensioner and a pelvic shield developed to prevent lap belt intrusion in to the pelvis-thigh flesh gap:

- Inclusion of the pelvic shield or belt pretensioner has an effect on rib deflections or spine kinematics.
- Inclusion of the pelvic shield has little effect on the pelvic kinematics or loading, although further component and sled tests are needed to confirm this observation.
- The pelvic shield eliminates belt intrusion into the thigh/pelvic flesh gap.

- Only the combination of pelvic shield and belt pretensioner together has a small effect on pelvis kinematics but further sled tests would be needed to validate this.

Effect of variation in WorldSID impact location:

- Rotating the WorldSID by 10° from the direction of impact has marginal effect on thorax response mainly due to variation in the upper rib to arm interaction.
- Rotating the WorldSID by 20° from the direction of impact has a major effect on thorax response, effectively increasing rib stiffness and reducing the rib deflection significantly. This suggests that the IR-TRACC system does not give a true measurement of maximum rib deflection under oblique loading conditions. Further component and sled tests would be required to quantify this behaviour.

Effect of variation in velocity profile:

- WorldSID is less sensitive than EUROSID-1 to small variations in the velocity profile after the initial peak.

3.2.2 Thorax Sensitivity Tests

The Thorax Sensitivity tests were conducted with a Part 572 pendulum of 23.4 kg at various angles and offsets relative to a pure lateral mid-thorax impact on the thorax. The dummy was seated in an automotive seating position according to UMTRI {2}. It was found that:

- The WorldSID thorax was very sensitive to impact angle and offset. Variations in measured rib deflection of up to 30 % and in acceleration of up to 50 % were observed for tests in the range -20° to +20° obliquity and +75.mm to -75 mm offset. Both of these measures would normally be used in injury assessment.
- It is not known if this behaviour is biofidelic, but it is suggested that such dummy behaviour is inappropriate.
- The variability implies that the dummy cannot indicate the true severity of an impact if direction and offset data is not available.
- Lateral and oblique impact tests to a single, isolated WorldSID rib should be undertaken in order to investigate angular sensitivity further, to determine whether the rib itself or the deflection measurement technique need to be improved.
- Certification of individual ribs is essential in order to ensure equal stiffness and dynamic performance, since the assessment of vehicle performance can be obtained from any single rib measurement.

3.3 Biofidelity Tests

3.3.1 Shoulder Biofidelity Tests

The shoulder biofidelity tests replicated the PMHS tests undertaken in WP2 of the SIBER project, which were designed to assess the response of the human shoulder to impacts at various angles. Shoulder tests were conducted on the dummy shoulder fitted with the half arm. The impact velocities were 2 $m.s^{-1}$ and 6 $m.s^{-1}$. The impact directions were lateral, 15° forward and 15° rearward of lateral using an impactor of 23.4 kg. The impacts were recorded on high-speed film and shoulder motion was analysed in 3 dimensions. Impactor accelerations were recorded.

Not all of the PMHS tests were completed at the time of the dummy tests and the remaining PMHS tests need to be conducted in order to be able to derive reliable biofidelity corridors and draw firm conclusions regarding the biofidelity of the WorldSID shoulder. However, from comparison with the initial PMHS biofidelity analysis, the following conclusions were made:

- Impact force was close to that of the PMHS;
- The WorldSID dummy had a more biofidelic response in oblique impacts in comparison to that of the EUROSID-1 in term of impact force;
- The dummy IR-TRACC shoulder deflection measurement was less than the true shoulder deflection due to the deflection of the arm. The shoulder deflection was found to be between 12 and 21 mm greater than the IR-TRACC measurement;
- For low to medium impact speeds, the arm deflection reached 18 ± 1.2 mm on average without influence of the impact conditions (impact angle and speed); for the highest velocities (test LWE 10), it reached 27 mm;
- At the 4 m.s^{-1} impact condition, the WorldSID shoulder deflection was close to the ISO corridor;
- For the 6 m.s^{-1} impact condition, the normalised dummy shoulder deflection was greater than that of the cadaver in absolute value, but it was equivalent in percentage of shoulder breadth compressed if raw data is considered.

3.3.2 Lumbar Spine Biofidelity Tests

The lumbar spine tests again replicated PMHS biofidelity tests undertaken in WP2 of the SIBER project. The tests were conducted with a spring propelled guided impactor of 23.4 kg on the thorax at 4.0 m.s^{-1} and the pelvis at impact velocities of 3.4 and 6.6 m.s^{-1}. Targets were fixed to the dummy at the spine and the pelvis according to UMTRI anthropometric co-ordinates {2}. The position of all the targets was recorded with a FARO arm after positioning of the dummy. Three-dimensional film analysis was performed to study the target trajectories and compared to the PMHS response. Again, the remaining PMHS tests are required for final conclusions to be drawn, but the initial analysis showed:

- At the 6.6 m.s^{-1} pelvic impact condition, WorldSID sacrum acceleration was comparable with that of the PMHS, but it seemed that the de-coupling between the dummy thorax and pelvis was slightly too high as the T12 accelerations were too low;
- At the 3.4 m.s^{-1} pelvic impact condition, the maximum values of the WorldSID sacrum acceleration were not sufficient and the de-coupling between the pelvis and the thorax decreased all the T12 accelerations.

3.3.3 Heidelberg Thorax and Pelvis Biofidelity Tests

Heidelberg sled tests were conducted according to the EEVC test specification [Roberts et al., 1991] at 7.6 m.s^{-1} in to a rigid wall and at 10.3 m.s^{-1} in to a padded wall. The latter test was conducted since the WSU padded wall sled test results with the WorldSID Prototype, which had been conducted earlier, showed signs of the padding bottoming out, resulting in high forces registered on the force plates. Recent tests have shown that the APR padding, kept in stock by TRL, still meets the requirements. The Heidelberg tests were conducted with two dummy build configurations of experimental parts in the pelvis and thigh regions of the dummy:

- Configuration 1: modified thighs with a more biofidelic mass distribution (low mass, uninstrumented femurs and dense thigh flesh), combined with the standard WorldSID pelvis (with the least stiff of the three available iliac wings);

- Configuration 2: standard thighs (including instrumentation), combined with a pelvis containing modified iliac wings, a smaller mock-up pubic symphysis load cell and two flexible pucks located between the dummy load cell and the iliac crests. The iliac wings were of the same material as those used in the standard pelvis.

The WorldSID dummy was found to be considerably less robust in the high-speed padded Heidelberg sled tests than the EUROSID-1 and ES-2. The main failures in the high-speed padded wall tests were rib failures, damage to sensor cables due to extreme rib distortion and damage to the arms. High-speed rigid wall tests, which form part of the EEVC biofidelity requirements, could not be attempted and not all of the test programme was completed due to the failures.

From the tests that were completed the following conclusions were made:

- In the low-speed rigid wall and high-speed padded wall Heidelberg sled tests, the biofidelity of the thorax was found to be fair and broadly comparable to that of EUROSID-1 and ES-2.
- In the high-speed padded wall Heidelberg sled tests, the biofidelity of the pelvis was found to be fair and comparable to EUROSID-1 and ES-2.
- In the low-speed rigid wall Heidelberg sled tests, the biofidelity of the pelvis was found to be a considerable improvement on that of EUROSID-1 and ES-2 with both dummy configurations. However, the peak force of the pelvis response still exceeds the EEVC corridor by up to 20%.

3.3.4 Pendulum Tests

Pelvis pendulum tests were conducted at velocities between 5 and 8 $m.s^{-1}$ according ISO TR9790 [ISO, 1997] for proof of concept of experimental parts. Four dummy configurations were tested, including the standard configuration.

The reduction of the rigidly coupled mass in the dummy pelvis structure had a positive effect on lowering the pelvis impactor forces. However, a single modification to the dummy, in either the pelvis or the leg was not sufficient to reduce the pelvis response adequately in the velocity domain of the dummy application. It was felt that both of the modifications would need to be incorporated into the dummy to obtain the optimum performance.

3.3.5 Neck Biofidelity Tests

The neck flexion and extension response was evaluated on a Part 572 pendulum according to the method of Irwin and Mertz [1997]. The tests were repeated with various hardness buffers installed in the anterior and posterior neck positions to select the buffer hardness for the best response and also to identify buffer hardness ranges required for possible response tuning. Upper neck forces and moments were measured with the WorldSID neck load cell and the head motion was obtained by high-speed video recording and analysis. It was concluded that:

- The prescribed pendulum acceleration for the Mertz moment-angle response in flexion seemed to be severe, as the chin touched the pendulum base. It should be considered if a less severe pulse, or initial velocity could be used;
- The extension pendulum test showed a bending moment of 100 Nm, which is 2 to 3 times too high, related to the extension and flexion corridor. It appeared that stiffer AP buffers could reduce the maximum bending moment. Thus a new test series with stiffer buffers was advised;
- No contact between head and neck or pendulum was found for extension;
- Chin pendulum contact was detected for pure frontal flexion at a pendulum velocity of 5 $m.s^{-1}$, and at 4 $m.s^{-1}$ for 45° oblique frontal impacts. What velocity level(s) would be allowed needs to be decided;

- Applying harder buffers could reduce the chance at rattling between the half-spherical screw and the neck interface plates. It was advised to check data of dummy application tests, such as full-scale car crashes, to see if test conditions similar to the pendulum test occur in the field of application.

3.3.6 Head Biofidelity Tests

Head drop tests were conducted with various head configurations, to assess the response of a simplified head core, to assess the influence of the head drop bracket and to provide additional test results as earlier test results conducted in different labs were contradictory. It was found that:

- The head impact response appeared to be consistent and within the PMHS related boundaries for the standard core, with WorldSID specific instrumentation and support tool. It was advised to use this configuration for certifying the skull impact attenuation;
- The mass of the head with the standard core and support tool was higher than the mass without the support tool, which results in 2.5% lower peak accelerations. The mass of the head with the simple core was less than the head with the standard core, which would probably result in 2.5 % higher peak accelerations.
- The impact response was less consistent when no support tool was used. Not all responses of the head with the simple core were within the PMHS related corridors. The contribution of accelerometer type, positional accuracy and mass could not be specified separately.
- The consequence of the sensitivity to impact location for full-scale HIC results should be given some consideration. The difference in skull energy absorption and a difference in generated angular rotation could cause this sensitivity.

3.4 Overall Conclusions

- Head biofidelity was consistent and good.
- Neck buffers were too stiff, leading to excessive neck bending moments in flexion and extension. Biofidelity of the prototype neck could be improved.
- Shoulder impact force biofidelity was an improvement on that of the EUROSID-1 dummy, but the shoulder IR-TRACC underestimated shoulder compression by 12 to 21 mm due to compression of the arm flesh.
- The thorax and abdomen IR-TRACCs do not give a true measure of rib compression in oblique loading conditions. Further component tests will be necessary to quantify the extent of this problem, but it is considered that, given the nature of dummy loading observed in a MDB tests, this characteristic may affect the dummy appropriateness for certification purposes.
- Certification of individual ribs must be undertaken to ensure performance under localised loading conditions.
- Ribs and rib IR-TRACCs were vulnerable to damage in sled tests in which the EUROSID-1 dummy would be expected to remain undamaged. However, in low speed tests the biofidelity of the thorax was fair.
- Coupling of the thorax and abdomen via the lumbar spine was too low at all impact speeds.
- In sled tests, the biofidelity of the pelvis was greatly improved compared to the EUROSID-1 and ES-2, although it still exceeded the maximum requirement (as defined by EEVC WG9) by 20%. This was thought to be due to leg interaction in the test and non-biofidelic distribution of the leg mass.

4 WorldSID Pre-production Dummy

4.1 Modifications to the WorldSID Prototype Dummy

As a result of the world-wide evaluation of the WorldSID prototype, changes were made to design the pre-production version of the dummy. These included modifications to improve the biofidelity rating, durability and handling, as shown below.

- Head (FTSS) - the thickness of the lateral head flesh was increased to 18 mm to improve the head biofidelity.
- Shoulder (FTSS) - the shoulder rib damping material thickness was increased from 4 mm to 9 mm to improve the biofidelity. The shoulder pad was split into two pieces to improve the durability.
- Abdomen rib damping material (FTSS) - the abdomen inner rib damping material thickness was increased from 4 mm to 6 mm to improve abdomen biofidelity.
- Half-arm (FTSS) -the half-arm was redesigned from a spring steel bone structure to a plastic bone. The shoulder plug was removed from the half-arm to improve the shoulder biofidelity. The shape was modelled to follow the AMVO UMTRI surface model more closely, but simplifications were made to obtain symmetry allowing one identical part to be used for left and right position.
- Pelvis (FTSS) - two flexible pubic buffers were added between the iliac crest and the pubic symphysis load cell to reduce the pelvis stiffness. The pubic buffers are rubber with moulded-on end plates. The pelvis and thigh flesh parts were merged into one piece to improve the interaction between the pelvis and the seat-belt. (The seat belt kept getting caught in the pelvis-thigh flesh gap in the prototype, providing non-biofidelic restraint of the dummy).
- Femur (Denton ATD) – the bone mass was reduced by 1.6 kg by removing one 6 axis load cell and placing the remaining load cell mid femur. The total mass was restored by increasing mass of the upper leg flesh to give a more biofidelic mass distribution and the coupling between the thigh flesh and the skeleton of the dummy was reduced. The number of DAS units in the femur was reduced to one per side. The DAS unit was mounted floating in the flesh, to reduce the coupled mass. The femur and pelvis modifications were intended to improve the pelvis biofidelity.
- Lower leg (Denton ATD) - the ankle joint and lower tibia flesh were redesigned to reduce the size of the ankle and to simplify assembly. This was not a biofidelity requirement, but the prototype ankle was considered to be too ‘fat’. Also the mass of the upper tibia was reduced in the knee area.
- Spine box (FTSS) - the spine box was redesigned to accommodate the DTS TDAS G5 on-board data acquisition system design. The interconnection between TDAS and dummy is a completely new design, allowing the user to insert sensor connectors freely in the connector block. A temperature sensor was mounted in the spine box and connected to a data logger in the DAS.
- Lumbar spine (FTSS) – is now a moulded rubber part.
- DAS (DTS) - the TDAS G5 system is an upgrade of the WorldSID Prototype dummy’s data acquisition system. The sensor modules, which were incorporated in the prototype load cells, are now incorporated in the G5 modules.
- Load cells (R.A.Denton) – all load cells are now of a conventional design, without integral sensor modules. They were redesigned to integrate larger connectors, which were needed due to the higher wire count needed without the sensor modules built in. A sensor ID was incorporated into each load cell for easy operation. The Dallas ID chip contains load cell ID as well as calibration information. A small, single axis pubic load cell was also developed.

Twelve pre-Production Dummies have been manufactured and purchased by organisations in Europe, North America and Japan. These will be subjected to a comprehensive evaluation in mid- to late-2003. This test programme includes an evaluation of the improved biofidelity of the pre-production dummy, although the emphasis will be placed on evaluating every other aspect of the dummy, particularly its suitability for use in full-scale regulatory testing.

4.2 European Pre-production Dummy Test Programme

In Europe, the pre-production WorldSID dummy was evaluated during the second half of 2003 by the SIBER consortium and by European vehicle manufacturers under the auspices of ACEA (Association des Constructeurs Européens d'Automobiles) and PDB (Partnership for Dummy technology and Biomechanics). The SIBER consortium goals were to:

- evaluate the biofidelity of the dummy to the draft IHRA side impact biofidelity requirements;
- evaluate the biofidelity of the dummy compared with the PMHS data generated within the SIBER project;
- evaluate the sensitivity of the dummy to different temperatures and impact conditions;
- undertake an accident reconstruction with the dummy;
- and perform out-of-position airbag tests.

ACEA and PDB undertook sled tests and full-scale car crash tests to various European and US regulatory and consumer test protocols (ECE R95, EuroNCAP, FMVSS 214, FMVSS 201, LINCAP). The results of the SIBER pre-production dummy test program are currently analysed and documented. A full report is expected in spring 2004.

4.3 Future Work

It is the intention of the WorldSID dummy task force that the design of the WorldSID dummy will be frozen in February 2004 and that the production version of the WorldSID dummy will be released in April 2004, along with all of the documentation necessary to enable the dummy to be adopted in side impact test procedures.

5 Discussion and Conclusions

This report gives an overview of the development of the 50th percentile WorldSID advanced side impact dummy. This dummy has been developed to meet worldwide requirements in side impact protection and to be superior to any existing side impact dummy current used in regulatory testing.

The EEVC WG12 has monitored the European contribution to the WorldSID development through the EC sponsored projects SID-2000 and SIBER. In particular the latter has contributed significantly to the assessment and improvement of the prototype and dummy. A full assessment of the pre-production dummy is scheduled before the end of the SIBER project by April 2004.

In summary, the following can be stated about the WorldSID development to date:

- The emphasis within the project has been on meeting the ‘good to excellent’ biofidelity target as defined by ISO; as a result, the WorldSID 50th male dummy prototype already experienced an improved ISO biofidelity over existing dummies such as SID, BioSID, EUROSID-1 and ES-2. Further improvements have already been reported for the WorldSID pre-production dummy.
- It should be noted that the reference used for biofidelity assessment is the ISO set of biomechanical corridors and the ISO biofidelity rating system. As indicated in chapter 2, the ISO test conditions do not exactly match the EEVC recommended requirements, nor the IHRA proposed set. It has been the intention of the WorldSID committee to make the dummy meet the IHRA proposed corridors in addition, however, lack of progress within the IHRA Biomechanics Working Group has prevent them in achieving this goal.
- The assessment of the prototype dummy in Europe was performed in a well co-ordinated fashion with the global effort. Most points of concern were addressed by the WorldSID Design Team in consecutive versions of the dummy. A number of concerns however were not addressed in the dummy so far, nor are intended to be addressed for the production version. The WG believes these issues however deserve to be further looked at in the near future:
  1. The thorax and abdomen IR-TRACCs do not give a true measure of rib compression in oblique loading conditions. Further component tests will be necessary to quantify the extent of this problem, but it is considered that this may affect acceptance of the dummy.
  2. Certification and/or evaluation of individual rib response should be considered to ensure performance under localised loading conditions.
  3. Ribs and rib IR-TRACCs were vulnerable to damage in sled tests in which the EUROSID-1 dummy would be expected to remain undamaged. Reliability of the dummy instrumentation and data acquisition system is an important concern.
  4. Coupling of the thorax and abdomen via the lumbar spine was believed to be too low at all impact speeds. Taking current T12 load discussions within EuroNCAP as an example, this should be further investigated.

Finally, since the dummy is far more advanced than any dummy before, sufficient day to day experience is necessary before more steps should be taken to promote the dummy for regulatory use. As a first step, the links with IHRA Side Impact protocol developments should be further strengthened, ensuring that the proposed new dummy and test protocols are evaluated together. In this respect, it will be of vital importance that work will start on the development of the small female version of the WorldSID dummy as soon as possible. The European commission has made funding available through the 6th framework IP APROSYS to contribute to a world-wide development of this dummy, however, success can only be guaranteed if sufficient support is given by governments and industry world-wide.

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