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Abstract The Q-Series dummies have been introduced into regulatory testing. Euro NCAP is also reviewing its child protection assessment procedures, possibly to include a Q10 in full-scale side impact testing. Full-scale lateral applications call for a better understanding of the side impact biofidelity of the Q10. To address this need, objectives were set to develop a side impact upgrade kit for the Q10 and evaluate the whole body biofidelity performance of the Q10 according to size-appropriate requirements.

A prototype Q10 shoulder and arm side impact kit was designed and manufactured, incorporating the addition of a shoulder load cell. The performance of the Q10, with and without the side impact shoulder kit, was then evaluated via scaled sled tests and pendulum impacts to the shoulder. The responses were compared with newly scaled biofidelity requirements.

The results demonstrate the benefit of the updated shoulder parts. Whilst the shoulder and arm side impact kit provides an improvement over the existing Q10 design with regard to performance in direct loading, the Q10 is not a dedicated device for side impact testing. As a consequence, the responses, even with the side impact shoulder kit, do not meet the biofidelity targets, remaining too stiff, particularly the pelvis.

Keywords Biofidelity, dummy design and evaluation, Q10, shoulder, side impact.

I. INTRODUCTION

The number of children killed or seriously injured in road traffic collisions has fallen steadily in most European countries over the last 10 years. United Nations (UN) Regulation No. 44, which is mandatory in the European Union (EU), has made a significant contribution by ensuring that child restraint systems meet minimum standards of performance in front impact collisions. Nevertheless, industry and regulators both agree that changes are needed if this progress is to be maintained.

In 2007, the UN Informal Group on child restraint systems was established by the Working Party on Passive Safety (GRSP) to develop a new UN Regulation on the approval of “Enhanced Child Restraint Systems”. The new regulation introduces the “i-Size” concept for child restraint to car compatibility, a stature-based system of classification for child restraints, a new family of child dummies (the Q-Series) and a side impact test procedure (amongst other innovations). Alongside the legislative developments, Euro NCAP carries out a child occupant safety assessment to ensure that manufacturers take responsibility for the children travelling in their vehicles [1]. As part of this assessment, Euro NCAP uses 18 month old and 3 year old sized dummies, placed in manufacturers’ ‘recommended’ child seats, in the frontal and side impact tests. Euro NCAP is planning on switching to the Q6 and Q10 in their frontal and side impact test procedures instead of the smaller Q1.5 and Q3 [2].

The UN-GRSP Informal Group has now asked the European Enhanced Vehicle Safety Committee (EEVC) to provide a new recommendation on the use of the Q-Series in legislation. The EEVC Steering Committee tasked EEVC WG12 with providing a report that supplements and updates a previous report prepared by EEVC WG12 (Biomechanics) and WG18 (Child Safety) in 2008 [3]. The scope of this new activity focusses on the use of the Q10 dummy (which was developed after the original WG12 and WG18 report) as well as broader advice on the interaction between the Q-Series dummies and the three-point seat belt (in non-integral child restraints), and the use of performance thresholds for chest compression and abdomen pressure.

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Biofidelity requirements for the Q-Series were introduced when the first dummies were developed. They were scaled from adult dummy requirements and were assessed by component-level (certification-type) tests. The performance of the dummies with respect to these biofidelity targets was investigated by EEVC WG12 and WG18 [3]. None of the Q-Series dummies met their targets for shoulder and thorax biofidelity in side impact; the dummies were too stiff by some margin. However, they were designed to be used in both front and side impact test procedures and it appears that front impact biofidelity was favoured (along with their overall durability). Despite their relatively poor side impact biofidelity, the dummies have demonstrated that they can be used to distinguish between child restraint systems with different levels of side impact protection [4].

Within the European Seventh Framework Programme (FP7) project EPOCh, two prototype Q10 dummies (Figure 1) were developed and subjected to a broad evaluation [5]. This assessment included biofidelity tests of the types associated with the other members of the Q-series family of dummies. At that time, the Q10 was found to be sensitive, repeatable and durable for impact loading in head drop, neck pendulum and full body pendulum tests. For frontal loading conditions it was stated that the dummy correlated well with most biomechanical targets specified in the Q10 design brief and performed in line with the Q-series family. However, for lateral impacts at the shoulder, thorax and pelvis, the force responses obtained exceeded the biofidelity corridors, with the dummy being too stiff in this impact direction. Hynd et al. commented that whilst not being in line with the biofidelity requirements, the cumulative response was consistent across the three body parts, implying that none of the body regions is overexposed in case of distributed side impact loading.

The authors have noted that concern has been expressed about the performance of the Q10 by some stakeholders; particularly with regard to its capacity to encourage improvements in car design and performance in the full-scale side impact test specified by Euro NCAP. So far, there is no evidence that the Q10 would not be able to discriminate between different restraint systems and side impact performance; although, it had been observed that the existing shoulder design could reduce loading to the thorax in side impacts. To improve the base of evidence on the Q10 and to address some of the comments and concerns over the use of this dummy in full-scale side impact tests, the Q10 side impact performance task force was setup.

As part of the adult range of dummies, the biofidelity requirements for the small female side impact dummy WorldSID-5F were more extensive than the basic certification-type biofidelity tests, typical for child dummies, and included full-body drop tests and sled tests. These full-body tests offer a more complete evaluation of the side impact biofidelity of a dummy than can be obtained by component-level tests alone. The aim of the Q10 side impact performance task force was therefore defined to evaluate the dummy in whole-body side impact biofidelity tests, similar to those used for the assessment of adult side impact dummy biofidelity. The research would compare the baseline dummy against a dummy equipped with a new side impact shoulder kit that is intended to improve its performance. This work is aligned with the activities on child dummies of EEVC WG12 and ultimately the findings will contribute to the efforts of EEVC WG12 (and to the UN Informal Group on child restraint systems). The objectives were defined as:

1. Develop a side impact shoulder kit for the Q10;
2. Determine size-appropriate whole-body side impact biofidelity requirements for the Q10 dummy;
3. Provide scaled test procedures for the evaluation of the Q10 against these requirements; and
4. Perform biofidelity performance tests of the Q10.



Fig. 1. Q10 dummy and equivalent finite element model.

II. HARDWARE DEVELOPMENT

Development of a side impact kit for the Q10 dummy

Based on the performance of the Q10 prototype (SBL-A) and production version (SBL-B), it was recommended to redesign the shoulder to lower pendulum forces in biofidelity tests and to include instrumentation to detect side protection systems included in modern vehicles.

In an attempt to define future improvements for side impact performance, a Finite Element (FE) study into possible concepts was conducted [6]. The initial focus was on the shoulder performance as this body region is the first to make contact with the vehicle restraint systems and affects the kinematics for other body regions (Figure 2). To avoid any negative effects on the frontal impact performance, it was proposed to introduce a side impact shoulder kit with a minimal number of components that are to be exchanged for side impact applications. The configuration evaluated through simulation included:

1. Omitting the lower arms;
2. Plastic upper arm bone replacing the aluminium of the frontal configuration; and
3. Softened shoulder rubber and arm flesh.

Simulated results for shoulder pendulum impact forces, as reported by Lemmen et al. [6], are depicted in Figure 3. Omitting the lower arm does not have a significant influence on the shoulder impact force as this part is remote from the impact location. When introducing a plastic bone in the upper arm (as used for the WorldSID-5F), shoulder forces were reduced. Softening of the shoulder rubber and arm flesh resulted in a further reduction, bringing the forces closer to the corridor but potentially also leading to some instability and interaction with the thorax.

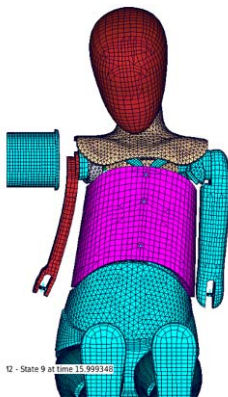


Fig. 2. FE model of Q10 dummy in deformed configuration with lower arms removed and upper arms with plastic bone (arm flesh in left arm made transparent for visualisation).

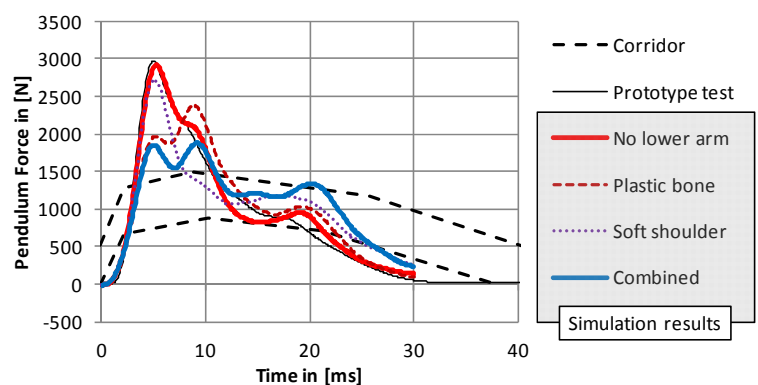


Fig. 3. Shoulder impact pendulum force versus time, prototype test result (for reference) and simulation results: No lower arm, No lower arm + Plastic upper arm, No lower arm + Soft shoulder rubber and all three measures combined.

Feedback on the above options was collected. The intention of a shoulder kit with a small number of parts was found to be acceptable. However, installation of the kit should not affect certification performance to ensure that recertification is not needed when swapping from front to side and vice versa. These requirements led to the decision to not change the shoulder rubber. Moreover, it would change the frontal thorax certification performance and introduce the possibility to make errors with the front and side configuration.

Based on the above, a prototype was realised (Figure 4 to Figure 6) consisting of:

1. A load cell to be mounted on the shoulder rubber end plate,
2. A new scapula fitted to accommodate the load cell,
3. An upper arm with an integrated plastic bone and flesh softer than the frontal arm, and
4. A universal joint that connects the arm to the shoulder load cell to allow for a thicker flesh at shoulder.

The side impact shoulder kit includes two locations to mount accelerometers. One accelerometer can be mounted on the shoulder rubber end and another one can be mounted at the modified lower neck interface ring, both measuring in the y-direction.

Special attention was given to the realisation of a shoulder load cell. The current load cell design consists of a single column with a capacity of 2,000 N in F_x , 4,000 N in F_y and 2,000 N in F_z direction, respectively. For frontal impacts there is a risk that the belt runs over the top of the upper arm. In such cases loads exceeding the capacity in F_x and F_z direction are to be expected. Therefore, the load cell cannot be used in frontal tests. In case the side impact kit is also proposed for usage in frontal tests, it is to be ensured that the load cell is replaced by a structural component that has substantially higher strength.

The resulting assembly including the shoulder accelerometer is depicted in Figure 5.

Figure 7 compares the contours of the side impact shoulder kit and the frontal dummy version. The kit was designed to meet the dimensions of the frontal version in the lateral direction. The outer arm plane is slightly flatter though in the side impact version to have a better defined interaction surface with the restraint systems.

Once the design was completed the Q10 FE model was updated to include a detailed version of the side impact kit. This version was used to predict loads that the dummy sustains during the intended biofidelity evaluations.



Fig. 4. Parts of the side impact kit.

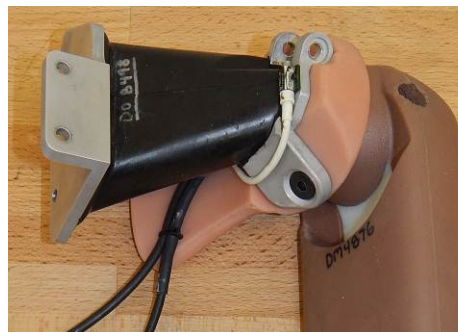


Fig. 5. Q10 Side impact kit with shoulder joint Ay accelerometer.



Fig. 6. Side impact kit installed on the dummy.

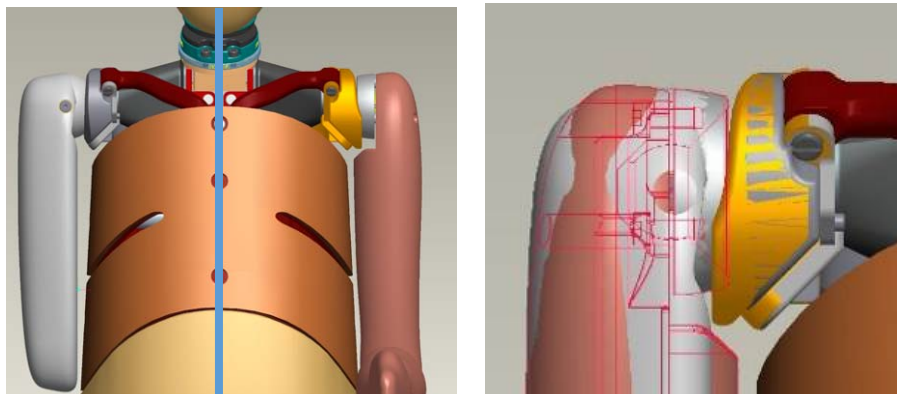


Fig. 7. Comparison of side impact kit (grey colour) and frontal dummy geometry (flesh colour and red line); side by side comparison (left) and overlay (right).

III. METHODS

Biofidelity evaluation of the Q10 dummy with side impact kit

A variety of pendulum tests can be used to assess biofidelity at the component level. In this study, lateral shoulder impacts were performed to investigate the influence of the new side impact parts when loaded directly. However, the main focus of the study was to assess the overall behaviour of the whole dummy when subjected to a lateral impact. Different datasets are available with which to assess the side impact biofidelity of dummies at the whole-body level. These sled tests are derived from Post-Mortem Human Subject (PMHS) experiments and provide corridors wherein the responses of dummies should lie in experiments of the same configuration. For simplicity, the datasets and test configurations are known and subsequently named after the laboratory that performed them:

1. University of Heidelberg (Heidelberg) [7-8];
2. Wayne State University (WSU) [8-9];
3. Medical College of Wisconsin (MCW) [10].

Typically, the subjects are seated on a side-facing rigid bench during an impact experiment. As the impact sled decelerates, the subject loads a series of force plates located adjacent to their torso, pelvis and legs. The general approach is consistent across these datasets, but there are differences in the arrangement of the force plates (i.e. in their number or size) and other factors, like the impact speed and padding of the force plates.

These datasets contain adult subjects only and require scaling to adjust the test configuration and the biofidelity requirements (to make them relevant for use with the Q10). Three load wall configurations were included in the test matrix in order to investigate separate loading of the shoulder (WSU configuration), indirect loading of the shoulder through the upper arm (MCW configuration) and combined loading of the shoulder and the thorax (Heidelberg configuration). In the original PMHS research, these were used in various set-ups: varying target impact speeds (mostly 6.7 m/s or 8.9 m/s), wall surfaces (rigid or padded), wall geometries (flat or with a single load plate offset) and wall orientations (lateral or oblique).

For the current research, speeds of 6.7 m/s or 6.8 m/s into a rigid wall were considered to be at a severity so as not to overload the Q10 dummy while providing sufficient PMHS results for comparison. Although possibly of great interest, higher speed tests into a padded wall in the WSU configuration could not be performed because padding material (paper honeycomb [8]) of the correct specification could not be procured. A flat wall set-up was used for all tests as no PMHS results from shoulder offset tests could be identified. Thorax, abdomen or pelvis offset tests were not expected to provide relevant results as they apply no direct loading towards the shoulder. The resulting test matrix contains 15 tests including four tests at lower speeds to ensure the dummy is not damaged in the rigid wall impacts at test speed (see Table II).

The impact wall configurations designed for mid-sized male surrogates were scaled to match the anthropometry of a 10.5 year old surrogate. Multiplicative scaling factors were derived by comparing average human anthropometric measurements from the UMTRI (University of Michigan, Transportation Research Institute) dataset [11] and the CANDAT (Child ANthropometric DATabase) dataset [12]. Angles between load wall elements remained unchanged. The vertical scaling factor, s_v , applied to dimensions along the seat back (height of plates and distance of plates from seat pan), was calculated as:

$$s_v = h_c / h_v = 747.6 \text{ mm} / 911.0 \text{ mm} = 0.8206 \quad (1)$$

where: h_c is sitting height to top of head (erect), CANDAT data, 10.5 year old

h_v is sitting height (erect), UMTRI standard anthropometry measurement, mid-sized male

The horizontal scaling factor s_h , subsequently applied to dimensions along the seat pan (width of plates and distance of plates from seat back), was calculated as:

$$s_h = l_q / l_v = 360.0 \text{ mm} / 431.8 \text{ mm} = 0.8337 \quad (2)$$

where: l_q is femur length, Q10, dummy measurement used as substitute for the femur length of a 10.5 year old, due to lack of appropriate measure in CANDAT dataset

l_v is distance of hip (point 66) to knee (point 67), UMTRI data, mid-sized male

Response requirements to determine the basic biofidelity of adult side impact dummies are specified in ISO Technical Report 9790 [5]. These lateral biofidelity requirements have been scaled for various sizes of dummies by Irwin et al. [13]. The Irwin study gives scaling formulas for sled tests, drop tests and pendulum tests for all body regions and for all types of responses like force, deflection, acceleration, displacement, etc. The Irwin study also gives anthropometry data for body segment dimensions and segment masses, which were the bases for development of the HIII family and the CRABI dummies [14-15]. Detailed scaling factors for all body segments and biofidelity parameters and the scaled biofidelity response requirements based on HIII anthropometry are available. However, the anthropometry of the Q-series dummy family was based on CANDAT data [16] and in this case the mid-sized male dimensions were taken from the UMTRI studies [17]. The scaling parameters required to generate the ISO biofidelity corridors for the shoulder, thorax, abdomen and pelvis are shown in Table I.

As with the original studies [6] and [18], a mass-based scaling [19] was used to adjust the MCW corridors for the Q10.

TABLE I

BIOFIDELITY RESPONSE SCALING PARAMETERS FOR 10.5 YEAR OLD, FROM ADULT 50 TH PERCENTILE		
Parameter	Lambda value	Source
<i>Bone elastic modulus (λE_{bone})</i>	0.875	[20]
<i>Erect seating height (λz_{torso})</i>	0.821	CANDAT & UMTRI [17]
<i>Torso stiffness (λk_t)</i>	0.718	calculated
<i>Total body mass (λm_{total})</i>	0.464	CANDAT & UMTRI [17]
<i>Shoulder and thorax pendulum mass (λm_p)</i>	0.374	[12]
<i>Ratio of sums of masses (λm_s)</i>	0.343	[17], [12]
<i>Equivalent mass scale factor (λm_e)</i>	0.507	calculated
<i>Pelvis stiffness (λk_t)</i>	0.718	same as torso
<i>Lower torso + Lower ext. mass (λm_{pelvis})</i>	0.460	[17], [12]

Experimental testing

The experimental testing of the side impact kit began with lateral pendulum impacts directed at the shoulder. Following these came the whole-body sled tests. In total, 15 sled tests were carried out in different load wall configurations (MCW, WSU and Heidelberg) and set-ups, including five initial tests at lower velocities to ensure the dummy was not damaged in the rigid wall impacts at the full test speed (Table II). The lower velocities were picked to span the range from zero to full speed and allow easy extrapolation, in case that was needed. The comparative tests conducted without the side impact shoulder kit involved the dummy with the original shoulder and arm parts, though the lower arms were removed to provide a closer match to the half arms of the side impact kit.

The tests were conducted on a bench of the Heidelberg-type, which was mounted on a deceleration sled system. This system was used previously for the evaluation of the WorldSID-5F biofidelity in the MCW configuration within the APROSYS project [21].

A load wall was installed at the impact side to which the scaled plates could be attached according to the scaled geometry as described earlier. The load wall consisted of a supported back plate to mount load cells in different configurations. The impact plates were mounted on the load cells according to the three configurations (Figure 8). To avoid head contact with the supporting structure above the uppermost plate, wooden distance plates were introduced between the back plates and the supporting wall. The dummy was positioned approximately one metre from the impact plates. As in the original tests, the Q10 dummy was seated against the seat back. The arms were positioned parallel to the mid-axillary line. The sled was accelerated to the desired impact velocity by a propulsion system and then decelerated by a hydraulic brake; the dummy continued to translate laterally against the impact plates. The deceleration pulse was chosen in a way that the sled was completely stopped before the dummy hit the load wall. To reduce friction between dummy and test bench during the deceleration of the sled, the seat, the back rest and foot rest were covered with Teflon. In addition, the dummy was seated on Teflon sheets (body and feet). Between the two Teflon layers, Silicon spray was used to further minimise friction.

Computational modelling

Computational modelling was used to support the experimental test programme and provide results from some configurations which could not be performed with the physical dummy due to project constraints and concern over durability. As an example, biofidelity tests of the Q10 without the side impact shoulder kit in the MCW configuration were conducted at speeds up to 5.8 m/s. Further testing was considered to be at too great a risk of damage to the dummy, without the side impact shoulder components. Therefore, simulation was used to match the physical test results and then predict dummy responses at the higher speed of 6.7 m/s. The results from the simulations are not discussed in detail within this paper.

In addition, simulation was used to investigate the influence of slight tilting about the torso x-axis. This led to the recommendation that all tests could be considered in the analysis as the levels of tilting seen were not expected to produce large deviations in measured values from test to test.

TABLE II
TEST MATRIX

	Test number	Side shoulder kit	Plate configuration	Sled velocity	Comment
1	Q10FMRFV1	no	MCW	3.8 m/s	Trial test at lower velocity
2	Q10FMRFV2	no	MCW	4.8 m/s	Trial test at lower velocity
3	Q10FMRFV3	no	MCW	5.8 m/s	Trial test at lower velocity
4	Q10FHRFV1	no	Heidelberg	5.8 m/s	Trial test at lower velocity
5	Q10FHRF01	no	Heidelberg	6.8 m/s	Biofidelity with original parts
6	Q10SHRFV1	yes	Heidelberg	5.8 m/s	Trial test at lower velocity
7	Q10SHRF01	yes	Heidelberg	6.8 m/s	Biofidelity with side shoulder
8	Q10SHRF02	yes	Heidelberg	6.8 m/s	Repeatability
9	Q10SHRF03	yes	Heidelberg	6.8 m/s	Repeatability
10	Q10SHRF04	yes	Heidelberg	6.8 m/s	Repeatability
11	Q10SWRF01	yes	WSU	6.7 m/s	Biofidelity with side shoulder
12	Q10SWRF02	yes	WSU	6.7 m/s	Repeatability
13	Q10FWRF01	no	WSU	6.7 m/s	Biofidelity with original parts
14	Q10SMRF01	yes	MCW	6.7 m/s	Biofidelity with side shoulder
15	Q10SMRF02	yes	MCW	6.7 m/s	Repeatability

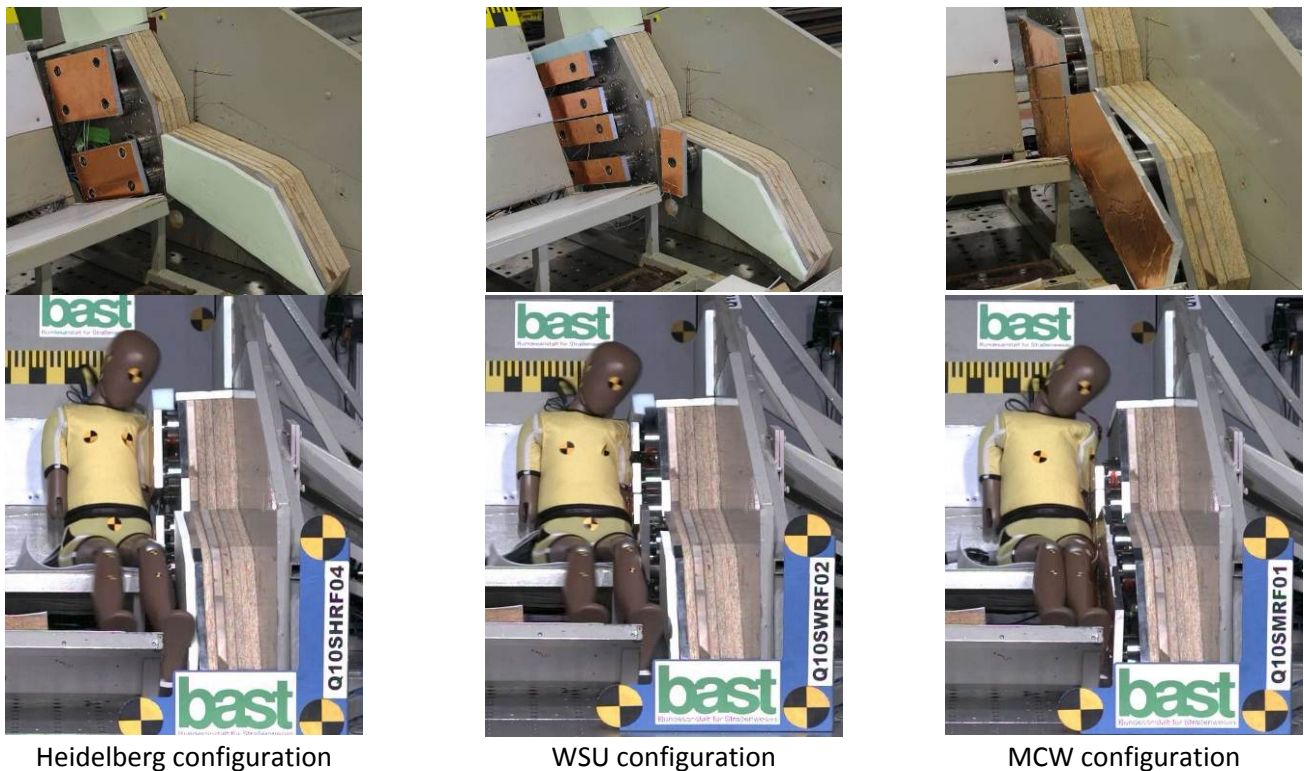


Fig. 8. Q10 dummy impacting different load wall configurations.

IV. RESULTS

The results from the evaluation testing of the side impact shoulder kit are presented in the following sections. These are compared with responses obtained with the Q10 in its normal configuration (without the side impact shoulder kit) though with the lower arms removed. They are also shown with the biofidelity requirements as scaled for the Q10. These are split by the type of load cell wall configuration used in the test; and prior to the sled tests, results from pendulum impacts to the shoulder are presented.

Pendulum tests

As an initial evaluation of the side impact kit, pendulum impact tests were carried out to the shoulder. These provide physical validation of the expected results derived in the initial design simulations. The scaled impact conditions replicating PMHS tests from the literature were provided through an 8.76 kg pendulum with a speed of 4.5 m/s. The pendulum force-time histories from these tests are shown in Figure 9. Findings from these tests were that:

- There is a negligible difference between test results with the Q10 prototype [5] and the Q10 production version;
- The two tests with the Q10 side impact shoulder kit show a 500 N reduction in maximum pendulum force with respect to the Q10 frontal arm results; and
- The time base of the pendulum force signal for the side impact shoulder kit increased by about 5 ms with respect to the Q10 frontal arm results, bringing it closer to the biomechanical corridor.

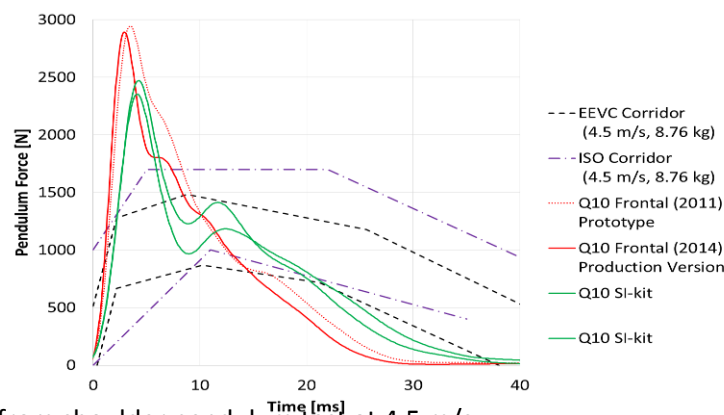


Fig. 9. Impactor forces from shoulder pendulum test at 4.5 m/s.

Sled tests in Heidelberg configuration

The thorax plate force responses from the 6.8 m/s tests into the rigid Heidelberg force plates are shown in Figure 10. The peak dummy acceleration measurements from the pelvis are shown in Figure 11. From Figure 10 it can be observed that with the original parts or when fitted with the side impact shoulder kit, the Q10 upper plate force responses fall nicely within the ISO corridor. The overlap of the green curves in this figure, showing the repeated side impact shoulder kit tests, demonstrates a good level of repeatability for the dummy in this measure. It can also be noted that the responses with the side impact kit are similar to those with the original parts, showing only a limited influence of the specific side impact shoulder and arm parts on the force at the upper plate.

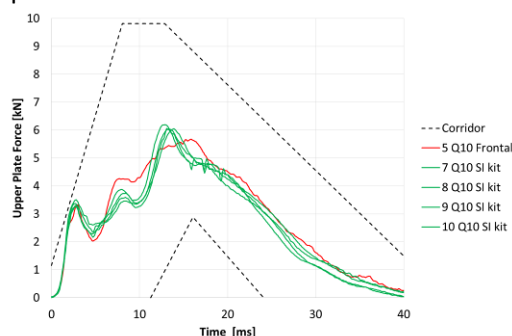


Fig. 10. Upper (thorax) plate forces from Heidelberg sled test at 6.8 m/s into the rigid load cell wall

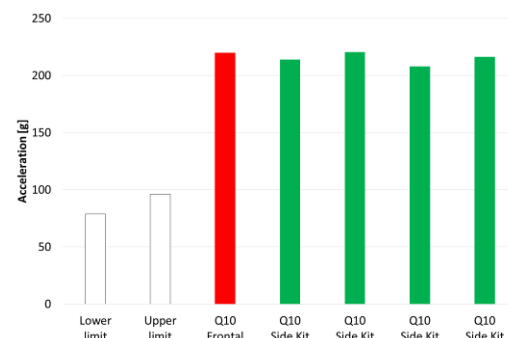


Fig. 11. Peak pelvis accelerations from Heidelberg sled test at 6.8 m/s into the rigid load cell wall

Unfortunately, the pelvis plate force signal for the test with the frontal configuration was found to be corrupt and could not be used in this analysis. However, peak pelvis accelerations for this condition showed similar results and can be seen in Figure 11. In either configuration the peak acceleration values are higher than the upper limit of the ISO biofidelity requirement.

Sled tests in WSU configuration

The abdomen and pelvis plate force responses from the 6.8 m/s tests into the rigid WSU force plates are shown in Figures 12 and 13. The dummy acceleration measurements from the pelvis are shown in Figure 14. Unfortunately, there is no biofidelity requirement for the shoulder and the thorax plate force for this WSU condition, though results from these force plates are shown in Figures 15 and 16. Figure 17 shows example forces from the new shoulder load cell, fitted as part of the side impact shoulder kit.

In the case of the WSU tests, the pelvis of the Q10 can again be seen to be too stiff, resulting in peak pelvis accelerations and pelvis plate forces which exceed the upper limits of the biofidelity requirements. However, the abdomen plate force response is slightly too low to fit within the corridor. At the level of the abdomen or pelvis, the influence of the side impact shoulder kit is minor, offering no substantial change in the biofidelity of the dummy based on these parameters. The shoulder plate data show a lowering in the forces in this region when using the side impact kit. In particular the first peak is reduced.

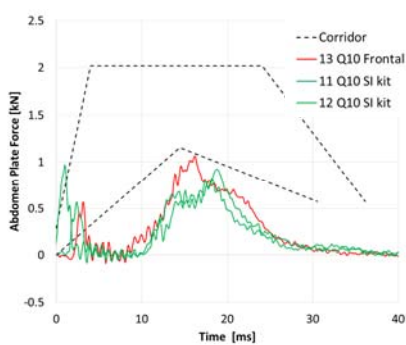


Fig. 12. Abdomen plate forces from WSU sled test at 6.8 m/s.

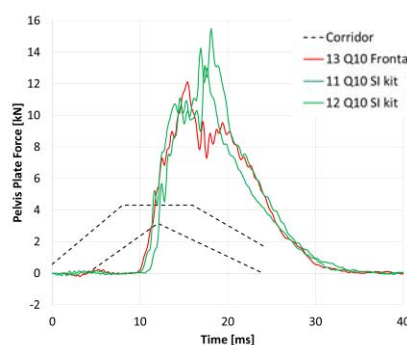


Fig. 13. Pelvis plate forces from WSU sled test at 6.8 m/s.

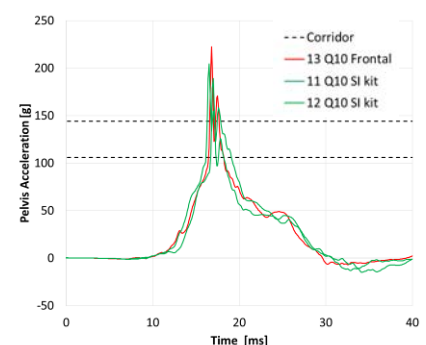


Fig. 14. Pelvis accelerations from WSU sled test at 6.8 m/s.

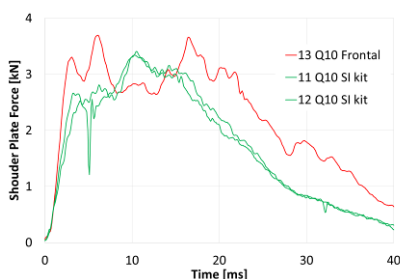


Fig. 15. Shoulder plate forces from WSU sled test at 6.8 m/s.

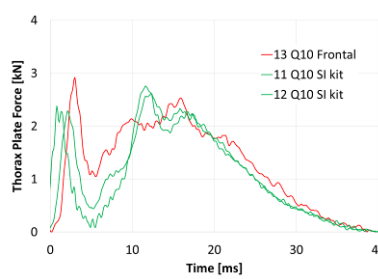


Fig. 16. Thorax plate forces from WSU sled test at 6.8 m/s.

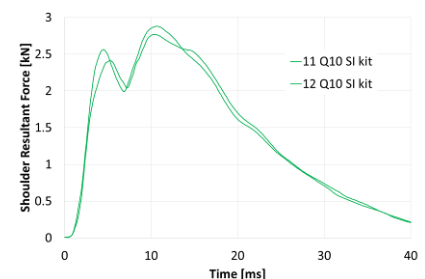


Fig. 17. Shoulder resultant forces from WSU sled test at 6.8 m/s.

Sled tests in MCW configuration

The thorax, abdomen and pelvis plate force responses from the 6.8 m/s tests into the rigid MCW force plates are shown in Figures 18, 19 and 20. With the MCW force plate responses, none of the dummy responses fits within the biofidelity corridors. However, the duration of the loading seems reasonable for all three load cell plates and the general shapes (modality) of the abdomen and pelvis plate responses show similarities with that of the corridor.

With the thorax plate, the initial peak in force is not a characteristic seen in the PMHS behaviour. However, the side impact kit helps to reduce this feature, bringing the shape of the response closer to that of the corridor. The unfortunate consequence of removing load from the thorax plate response in this way is that there is a higher peak force in the pelvis plate response moving that further from the requirements.

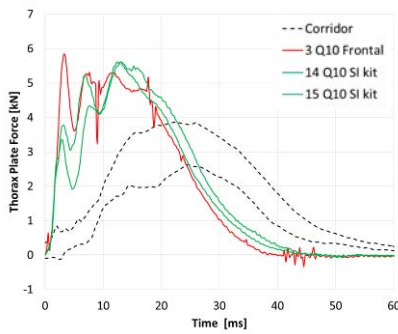


Fig. 18. Thorax plate forces from MCW sled test at 6.8 m/s.

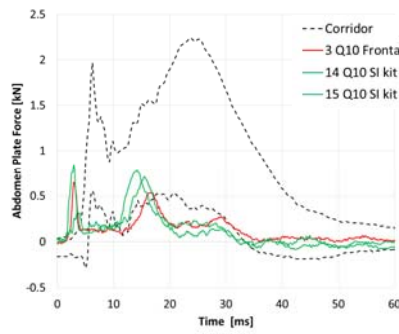


Fig. 19. Abdomen plate forces from MCW sled test at 6.8 m/s.

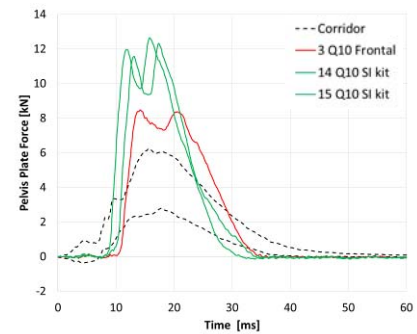


Fig. 20. Pelvis plate forces from MCW sled test at 6.8 m/s.

When considering the chest deflection measurements, the upper IRTACC output was compared with the upper chest deflection corridor (Figure 21) and the lower IRTACC output was compared with the middle chest deflection corridor (Figure 22). In both cases, the Q10 responses did not stay within the corridor boundaries. However, it is evident that the side impact kit has the effect of increasing the upper measurement and decreasing the lower measurement. This improves the peak deflection values measured by the dummy, making them both lie within the range of expected peak values from the biofidelity corridors, though the timing of the dummy response means the peak occurs too early.

The pelvis acceleration responses again demonstrate that the Q10 dummy is too stiff in this region to meet the whole-body side impact sled test requirements (Figure 23). It must be noted that the results shown for the original Q10 components were scaled from a lower speed test, assuming that deflection would be directly proportional to impact speed (as demonstrated with the WorldSID-5F [22]).

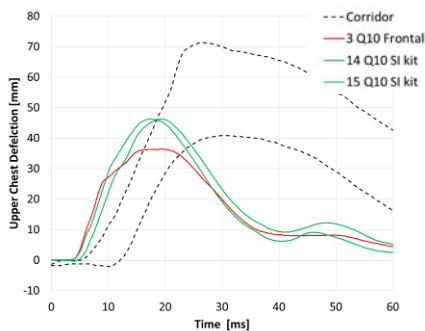


Fig. 21. Upper chest deflections from MCW sled test at 6.8 m/s.

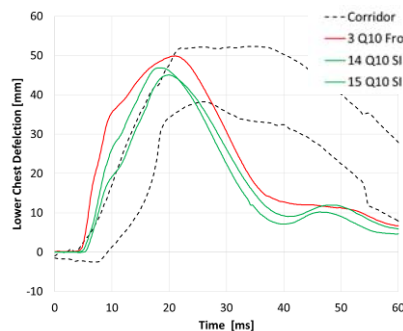


Fig. 22. Lower chest deflections from MCW sled test at 6.8 m/s.

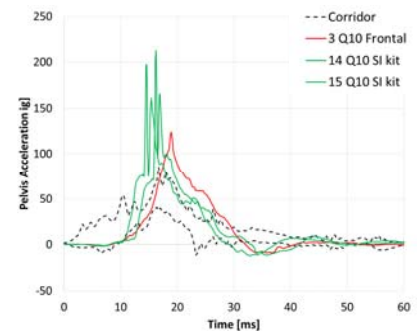


Fig. 23. Pelvis accelerations from MCW sled test at 6.8 m/s.

Figures 24 and 25 show resultant forces from the shoulder load cell and thorax plate forces, respectively, obtained from sled tests and numerical simulations. The simulation results generally correlate quite well with the test results, which was also found for other configurations modelled. In the testing it was observed that the dummy rotates slightly around the x-axis as it slides towards the load cell wall. This tilting ensures that the shoulder contacts the wall before the pelvis. To investigate the influence of this tilting, the simulations were run with the dummy sitting straight up or rotated three degrees around its x-axis just before impact. Results in Figure 24 shows that this rotation has very minor effect on the measured forces in the shoulder itself. Some influence is found on the thorax plate forces of Figure 25, showing scatter of the same magnitude as found in the physical test-to-test variations.

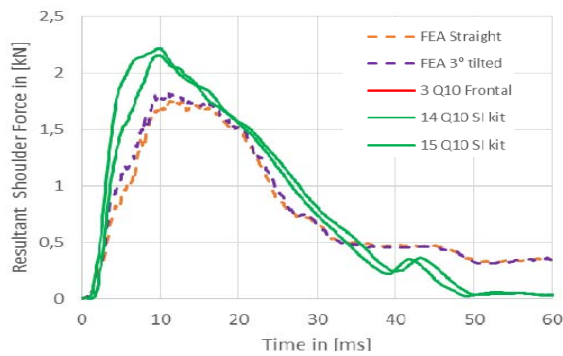


Fig. 24. Test data and simulation results for resultant shoulder loads in the MCW sled test at 6.8 m/s. Simulation results for 0 and 3 degrees of tilt.

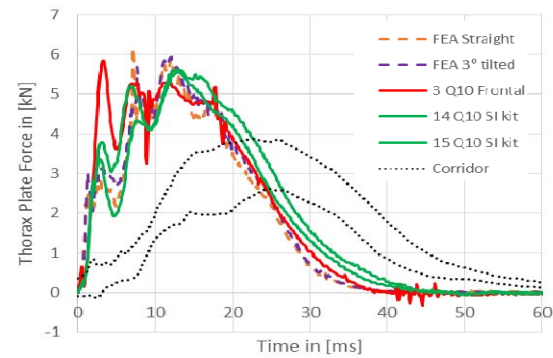


Fig. 25. Test data and simulation results for thorax plate loads in the MCW sled test at 6.8 m/s. Simulation results for 0 and 3 degrees of tilt.

V. DISCUSSION

Shoulder region – In the pendulum test evaluation, although peak shoulder forces do come down with the side impact kit modification, they have not been reduced sufficiently to fit within the corridors (either the EEVC corridor used as a design target or the scaled ISO 9790 corridor). To provide some context for this result, the equivalent test results for the WorldSID-5F Revision 1 dummy [23] are closer to the respective fifth percentile female corridor than the Q10 is to its corridor. Unlike the Q10, the WorldSID-5F was designed with a particular focus on side impact biofidelity and performance. The peak impactor force for the WorldSID-5F is only 15 to 20% higher than the upper boundary of the corridor, rather than 40 to 50% as with the Q10 fitted with the side impact kit. However, this should not detract from the fact that the side impact kit still offers some improvement in shoulder biofidelity over the baseline Q10, as assessed by this test.

Regarding the full body sled tests, minor influence of the side impact kit compared to the frontal dummy version is found on the upper plate responses. This indicates that the response is driven more by the dummy mass than by the local stiffness. The first contact between the dummy and the load cell wall is with the shoulder of the dummy and the uppermost force plate. Tests in the WSU configuration which includes a shoulder plate (but no corridors and not shown in the results) show a lowering in the forces in this region when using the side impact shoulder kit. In particular the first peak is reduced.

Thorax region – The Q10 thorax responses with or without the side impact shoulder kit are in the centre of the scaled corridor for the Heidelberg configuration. Here it can be noted that the thorax response of the WorldSID-5F lies at the top of the corridor [23], not so neatly through the centre of it as with the Q10. For the MCW tests on the other hand, the thorax plate responses are higher than the corridor for the Q10 (and further from it than the dedicated side impact dummies WorldSID-50M and ES-2re [24]). In contrast to side impact dummies, the Q10 does not have an abdomen designed to control deformation in lateral loading. For frontal applications the abdomen needs to allow for substantial dummy flexion and this was the dominating design priority for the Q10 abdomen. Other than the low foam compression stiffness, no further deformation control is applied in this region for side impacts. The lack of abdomen stiffness in the Q10 may contribute to the higher force responses in the thorax region.

The soft upper arm bone of the side impact shoulder kit results in a more compliant interaction in the thorax region. The metal bone of the original arm shielded the upper part of the thorax while bridging between the shoulder and the lower torso. Due to the flexible bone the shielding is reduced and the loading is distributed more evenly over the impacted area. As a result, the side impact kit shows an increase in the upper chest deflections and a reduction of the lower chest deflections, bringing results closer to the MCW biofidelity corridors.

Abdomen region – In the abdomen region, the Q10 dummy responses (with and without the kit) follow trends as observed in the PMHS tests. For the MCW tests, two peaks are observed and the timing is close to matching the PMHS corridors. However, the magnitude of the load level is lower than the corridor. This might be explained partially by the fact that the Q10 abdomen has no significant structural stiffness for lateral impacts. It is also known that the Q10 dummy has a relatively lightweight abdomen with mass apportioned into the sacrum. The stiffness and mass distribution are likely to be contributing factors in this result.

Pelvis region – In the pelvis region higher forces and accelerations are observed. This region of the dummy is too stiff; a problem which is not evident with the WorldSID-5F [23]. The effect of the side impact kit at this level in the dummy is negligible based on these results. Here it is to be noted that design changes in this region were explicitly outside of the scope of this study. However, the character of the signals (trends) matches that of the response requirements quite well. The Q10 has a relatively low mass abdomen compared with the human. Due to this, mass was concentrated in the sacrum to meet the mass distribution target for the lower torso. This may help explain the lower abdomen loads in some cases and the higher pelvis loads. It may not be just that the pelvis is too stiff.

Although it was deliberately and specifically set to be outside of the scope for this research, further updates to the dummy to improve side impact biofidelity might need to consider modifications to the pelvis region. However, it should be realised that this may affect large portions of the dummy, including femurs, pelvis structure and lumbar spine. In which case, frontal dummy performance would be altered.

Dummy durability – During the test programme of 15 severe sled impact tests against rigid walls and over 60 pendulum tests none of the dummy parts failed, indicating that the proposed design is robust and durable.

Limitations – There were a number of contributory factors which meant that a limited set of tests with response corridors could be reproduced for the evaluation of side impact biofidelity of the Q10. This was mainly because of availability of appropriate parts like padding materials and more advanced test fixtures like the MCW oblique configuration [25]. Here it should be noted that identical issues have been faced for other dummies [21].

The testing here supplements certification-type biofidelity data by adding full-body sled tests. However, in this evaluation, no tests were performed under conditions expected to be associated with final use of the dummy in side impact. Therefore it remains to be seen if the side impact shoulder kit improves the suitability of the Q10 for use in side impact testing applications.

VI. CONCLUSIONS

The Q10 was developed within the EPOCH Project, extending the upper age of the Q-Series of dummies. However, more information was sought regarding its side impact biofidelity to support implementation in new applications. To address this research need, a small task force was set up and has completed the whole-body side impact sled tests, described above, with the Q10 dummy.

To be able to assess the biofidelity in such sled tests, the test conditions and biofidelity requirements were scaled for the anthropometry represented by the dummy. Alongside the biofidelity evaluation, the opportunity was taken to design, develop and assess the potential of a side impact kit to improve the behaviour of the shoulder of the dummy to lateral impacts and to enhance its measurement capabilities with regard to side impact loads with a shoulder load cell and two additional accelerometer locations. The FE model that served as the basis for the hardware development provided results which correlated well with the physical test data and offered additional insight when analysing the test data.

The side impact shoulder kit was effective in reducing the stiffness of the shoulder and improving the biofidelity of this area of the dummy to direct impacts. In the whole-body biofidelity sled tests, the side impact kit components seemed to provide a small improvement in the transmission of force to the thorax. However, due to the limitations of the scope, the side impact shoulder kit does not address the balance of force exerted through the abdomen and pelvis regions and the observation that the pelvis is stiffer than the biofidelity requirements.

VII. ACKNOWLEDGEMENT

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VIII. REFERENCES

- [1] Euro NCAP. Assessment protocol – child occupant protection, Version 6.4.1. Internet: <http://www.euroncap.com/files/Euro-NCAP-Assessment-Protocol---COP---v6.4.1---0-aa39016a-16db-4441-82db-3e3a71c3443f.pdf>, December 2013 [10 March 2013].
- [2] van Ratingen M. Roadmap to Implementation. Internet: <http://prezi.com/ha8ri-zfjhu/h/euro-ncap-roadmap->

to-implementation/, March 2012 [10 March 2013].

- [3] Wismans J, Waagmeester K, et al. Q-dummies report: advanced child dummies and injury criteria for frontal impact. Previously available from the internet: <http://eevc.org/publicdocs/publicdocs.htm>, 2008.
- [4] Visvikis C, Le Claire M. Evaluation of child dummies – Final report, (Report number PPR165), Published Project Report, TRL, Wokingham, UK, 2003.
- [5] Hynd M, McGrath M, Waagmeester K, Salters E, Longton L, Cirovic S. EPOCH Project dissemination. *Protection of Children in Cars Conference*, 2011, Munich, Germany.
- [6] Lemmen P, Waagmeester K, et al. Development of the Q10 10 Year-Old child crash test dummy, *24th International Technical Conference on Experimental Safety Vehicles (ESV)*, 2013, Seoul, Korea.
- [7] Marcus J, Morgan R, Eppinger R, Kallieris D, Mattern R, Schmidt G. Human response to and injury from lateral impact. *27th Stapp Car Crash Conference*, 1983, San Diego, CA, USA.
- [8] ISO/TC22/SC12/WG5. Road Vehicles – Anthropometric side impact dummy – Lateral impact response requirements to assess the biofidelity, TR 9790, 1997.
- [9] Cavanaugh J, Zhu Y, Huang Y, King A. Injury and response of the thorax in side impact cadaveric tests. *37th Stapp Car Crash Conference*, 1993, San Antonio, Texas, USA, pp. 199-221.
- [10] Maltese M, Eppinger R, Rhule H, Donnelly B, Pintar F, Yoganandan N. Response corridors of human surrogates in lateral impacts. *Stapp Car Crash Journal*, 2002, 46:321-351, Ponte Vedra Beach, Florida, USA.
- [11] Schneider L, Robbins D, Pflueg M, Snyder R. Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family, *University of Michigan, Transportation Research Institute*, Michigan, USA, 1983.
- [12] Waagmeester K, Burleigh M, Lemmen P. Biomechanical requirements and design brief. European Commission, EPOCH Project, Work Package 1, Task 1.2, Deliverable D1.2, Internet: <http://www.epochfp7.org/Publications.aspx>, 2009 [11 March 2014].
- [13] Irwin A, Mertz H, Elhagediab A, Moss S. Guidelines for assessing the biofidelity of side impact dummies of various sizes and ages. *Stapp Car Crash Journal*, 2002, 46:297-319, Ponte Vedra Beach, Florida, USA.
- [14] Irwin A, Mertz H. Biomechanical bases for the CRABI and Hybrid III child dummies. *41st Stapp Car Crash Conference*, 1997, Lake Buena Vista, Florida, USA.
- [15] Mertz H, Jarrett K, Moss S, Salloum M, Zhao Y. The Hybrid III 10-Year-old dummy. *45th Stapp Car Crash Journal*, 2001, 45:319-328, San Antonio, Texas, USA.
- [16] van Ratingen M, Twisk D et al. Biomechanically based design and performance targets for a 3-year old child crash dummy for frontal and side impact. *Child Occupant Protection 2nd Symposium*, 1997, Orlando, Florida, USA.
- [17] Robbins D. Anthropometric Specifications for Mid-sized Male Dummy, Volume 2. Final Report UMTRI-83-53-2. *University of Michigan Transportation Research Institute*, Michigan, USA, 1983.
- [18] Yoganandan N, Pintar F, Gennarelli T. Small female-specific biomechanical corridors in side impact. *Proceedings of the IRCOBI Conference*, 2004, Graz, Austria.
- [19] Mertz H. A procedure for normalizing impact response data. *SAE Government/Industry meeting and exposition*, 1984, Washington, D.C., USA.
- [20] Carroll J, Pitcher M. The development of injury risk functions. European Commission, EPOCH Project, Work Package 1, Task 1.3, Deliverable D1.3 Internet: <http://www.epochfp7.org/Publications.aspx>, 2009.
- [21] Eggers A and Schnottale B. WorldSID 5th percentile dummy Rev1 sled tests (NHTSA configuration). APROSYS Project Technical report, Deliverable 5.2.9 Appendix BAst (AP-SP52-0068), 2009.
- [22] Carroll J, Goodacre O, Hynd D, Petitjean A. Testing of the WorldSID-5F to support injury risk function development and assessment of other performance issues. *23rd International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2013, Seoul, Korea.
- [23] Been B, Waagmeester K, Trosseille X, Carroll J, Hynd D. WorldSID small female two-dimensional chest deflection sensors and sensitivity to oblique impact. *21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 2009, Stuttgart, Germany.
- [24] Rhule H, Moorhouse K, Donnelly B, Stricklin J. Comparison of WorldSID and ES-2re biofidelity using an updated biofidelity ranking system. *21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV)*, 2009, Stuttgart, Germany.

- [25] Yoganandan N, Humm JR, Pintar FA. Force corridors of post mortem human surrogates in oblique side impacts from sled tests. *Annals of Biomedical Engineering*, 2013, 41(11):2391-8.