Assessing Lap Belt Path and Submarining Risk in Booster Seats: Abdominal Pressure Twin Sensors vs. Anterior-superior Iliac Spine Load Cells.

Costandinos Visvikis, Jolyon Carrol, Mark Pitcher, Kees Waagmeester

Abstract Q-Series dummies, combined with hip liners and Abdominal pressure twin sensors have shown limited capacity to discriminate differences in child booster seats. They offer little incentive, therefore, to optimise lap belt path. Anterior-superior iliac spine load cells measure force (Fx) and moment (My) at each ilium. They measure dummy-belt interaction in the lower region of, and below, the abdominal pressure twin sensors. This study investigated whether anterior-superior iliac spine load cells (compared with the abdominal pressure twin sensors) are sensitive to the position of the belt over the pelvis, and whether they have potential to predict booster seat performance.

Both sensors detected poor restraint in extreme cases with clear submarining. However, neither sensor fully distinguished undesirable belt interactions in which submarining was unclear (albeit suspected in some cases). This possibly reflected the dummy's capacity to display full submarining. Although significant pelvic displacement (with reclined torso) was observed, the belt may have stayed on the iliac crests. The anterior-superior iliac spine load cells offered complimentary information to the abdominal pressure twin sensors, but essentially duplicated their findings in our experiments. Characterising their response in a larger programme of experiments would help interpret their output and/or develop robust metrics. Nevertheless, measuring anterior-superior iliac spine loads has the potential to encourage booster designs that keep the belt low on the pelvis.

Keywords Abdomen injury, abdominal pressure twin sensors (APTS), anterior-superior iliac spine (ASIS) load cells, child occupant protection, Q-Series dummy.

I. INTRODUCTION

The abdomen is vulnerable in vehicle collisions because it receives very limited protection from the skeletal system. This means that serious injuries can occur with relatively low levels of loading [1]. Furthermore, the outcome can be compromised by delays in diagnosis because abdomen injuries resulting from blunt trauma (which is typical of vehicle occupants) may not display immediate symptoms [2]. The seat belt is the main source of abdomen injuries in restrained occupants [3]. The belt compresses the anterior surface of the abdominal wall and the underlying organs and soft tissues, leading to injury [4]. When restraining an occupant correctly, the lap part of a seat belt is intended to pass over the top of the thighs. The anterior-superior iliac spines (ASISs) of the pelvis serve as an anchor point for the belt, help to maintain its position during a collision and avoid excessive compression of the abdomen. However, the seat belt geometry in a car is designed for adults. Children cannot achieve a good fit of the belt, which, coupled with their small, under-developed pelvis, can increase their risk of receiving an abdomen injury [5]. Booster seats have proven to be effective in reducing the risk of abdomen injury in older children compared with the adult seat belt [6]. Nevertheless, abdomen injuries are still observed in children using these child restraints systems (CRS) [7-8].

The assessment of abdomen injury risk in United Nations (UN) Regulation No. 129 (on Enhanced Child Restraint Systems) is made with a pressure-based criterion. Abdominal Pressure Twin Sensors (APTS), within the abdomen of the Q-Series, measure loading from the restraint system in the front impact test. The sensors have been evaluated extensively and a pressure-based injury criterion developed from accident reconstruction [9-10].

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The Q-Series dummies were developed with superior biofidelity and injury assessment capabilities, compared with the P-Series (their predecessor in child restraint approval legislation) [11]. Nevertheless, the capacity of the dummies to submarine and generate meaningful loading to the abdomen has been the subject of considerable international effort [12]. Two principal issues have emerged: firstly, the gap between the legs and pelvis, which traps the belt, regardless of booster design, and secondly, the extent to which the pelvis can rotate rearwards, which is thought to be an important part of the submarining mechanism in real children [13]. The first issue has been solved, to some extent, by using a hip liner (available for the Q3, Q6 and Q10). This accessory has shown promise in preventing belt entrapment and appears to facilitate submarining and loading to the APTS (under certain conditions in which it might be expected) [14]. However, the dummy, the APTS, or perhaps more accurately, the regulatory procedure in its entirety, still does not discriminate differences fully among booster seats [15]. There might be a minimum pulse threshold and/or a maximum belt tension threshold that facilitate submarining and abdomen loading [16]. Alternatively, the APTS may lack some measurement sensitivity in the region close to, or just above the ASIS, because they do not descend (with their sensitive area) fully into the base of the abdomen [17]. Previous attempts to develop criteria using traditional dummy metrics and/or kinematic measures were not particularly successful with the Q-Series [18-19]. The APTS therefore remain the principal means of detecting abdomen injury risk.

The ASIS load cells are available as prototypes. They measure Force (Fx) and Moment (My) at each ilium of the pelvis. They have the potential to provide additional information to the APTS about the behaviour of the lap belt during an impact [20]. For example, they may be well-suited to detecting unfavourable belt interactions and subsequent submarining in a body region not covered by the APTS. ASIS load cells have been used in other dummy families, but are a relatively new development for the Q-Series. Their use has not, to our knowledge, been reported previously beyond a handful of tests. This study aimed to compare the APTS and ASIS load cells and to specifically to understand what additional information the ASIS load cells might provide about the position of the lap belt and its interaction with the pelvis and/or abdomen.

II. METHODS

Experiment Overview

Fourteen front impact experiments were carried out on a deceleration sled at TRL Child Safety Centre in the UK. TRL is an accredited Technical Service for the type-approval of child restraint systems to UN Regulation No. 129. The tests were performed according to the procedure specified in the 02 series of amendments to UN Regulation No. 129. The regulatory test conditions comprise an impact speed of 50^{+0}_{-2} km/h and a deceleration corridor that peaks between 20 g and 28 g. The experiments are summarised in Table I. All measurement and data analysis conformed to ISO 6487.

Dummies and Instrumentation

Two fully-instrumented Q-Series dummies were used: a Q6 and a Q10. Most booster seats approved to UN Regulation No. 129 will be tested with the Q3 (due to the minimum child stature likely to be declared for boosters by manufacturers). However, ASIS load cells are not currently available for this dummy. Only the Q6 and Q10 enabled a comparison to be made between the APTS and ASIS load cells.

Both dummies were certified and prepared for testing in line with the regulatory procedure. Accordingly, each dummy was equipped with production versions of the APTS produced by Transpolis, France and hip liners produced by Humanetics, Germany. Hip liners are a relatively new accessory to prevent the lap part of the seat belt from becoming trapped in the gap between the legs and pelvis. They are defined in the drawing packages of the Q3, Q6 and Q10 dummies administered by the United Nations Economic Commission for Europe and are mandatory components for all regulatory testing. The dummies were also equipped with ASIS load cells produced by Humanetics. These comprise twin (two-axis) load cells installed in the ASIS of the dummy pelvis. They measure the longitudinal force on the ASIS (Fx) and the moment about the lateral axis (My).

TABLE I
TEST MATRIX

Model	Booster Installation	Lap belt guides	Lap belt fit[I]	Dummy
No booster	3PT belt	None	Poor	Q6
Booster A	ISOFIX and 3PT belt	Symmetrical	Good	
Booster B	ISOFIX and 3PT belt	None	Poor	
Booster C	ISOFIX and 3PT belt	None	Poor	
Booster D	ISOFIX and 3PT belt	None	Poor	
Booster E	3PT belt	Asymmetrical	Poor	
Booster F	3PT belt	None	Poor	
No booster	3PT belt	None	Good	Q10
Booster A	ISOFIX and 3PT belt	Symmetrical	Good	
Booster B	ISOFIX and 3PT belt	None	Poor	
Booster C	ISOFIX and 3PT belt	None	Good	
Booster D	ISOFIX and 3PT belt	None	Poor	
Booster E	3PT belt	Asymmetrical	Poor	
Booster F	3PT belt	None	Poor	

[I] Lab belt fit is illustrated in Fig.3 and assessed in Fig. 4

There are no agreed performance criteria or thresholds for use with the ASIS load cells in the Q-Series dummies. However, based on the loading diagram shown in Fig. 2, Humanetics, has proposed a *red zone* to indicate a region of submarining risk [20]. The boundary of the zone is set at My/Fx = 10. However, this is only a guide to interpreting the measurements and has not been validated.

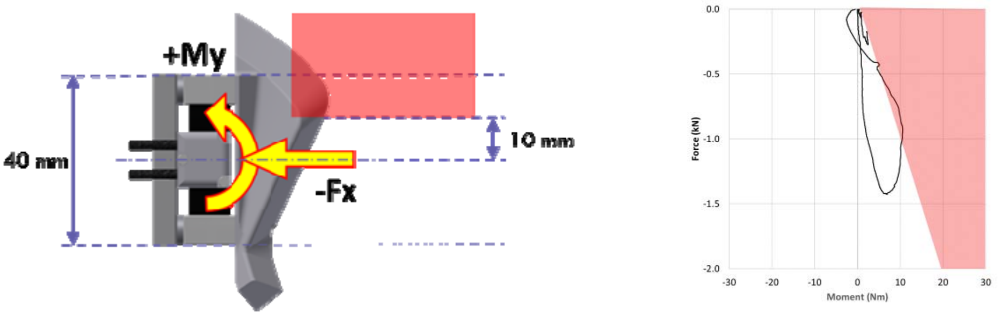
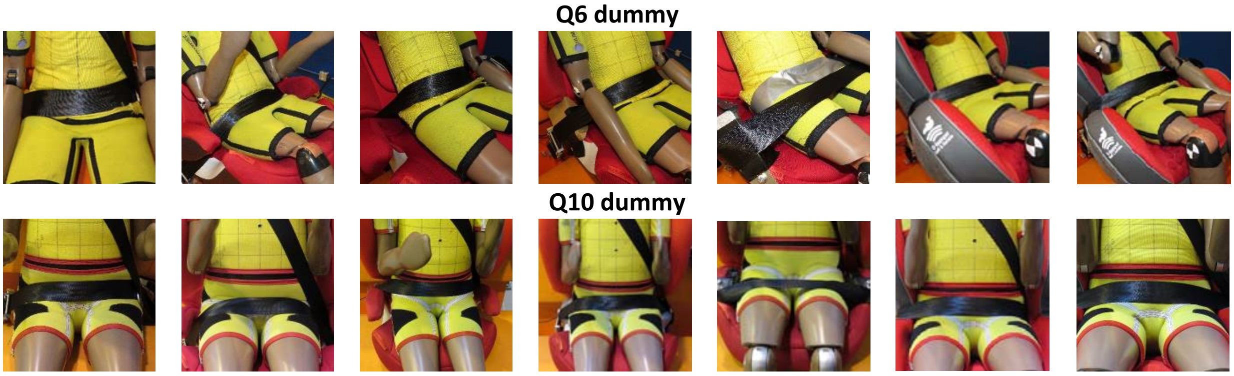


Fig. 2. ASIS load cell force diagram and proposed region of submarining risk.

Booster Seat Selection and Static Lap Belt Path Assessment

Baseline experiments were carried out with each dummy seated directly on the test bench (with no booster seat). These were supplemented with experiments with booster seats selected and/or adapted to generate different belt paths over the pelvis, i.e. high, low, forwards, and different belt guidance, i.e., none, symmetric, asymmetric. Adaptations were made to approved booster seats because it was not possible to identify seats with a range of static belt paths. The main European consumer test of child restraints, undertaken by Stiftung Warentest and the German Automobile Club (ADAC), assesses the *belt routing* of booster seats. However, the test and assessment protocols and detailed results are not readily available.

Two European booster seats type-approved to UN Regulation No. 44 formed the basis for the study. Booster A featured lap belt guides on both sides of the seat that positioned and maintained the belt over the pelvis and thighs. Booster E guided and maintained the lap belt on one side only. These boosters were then adapted by removing or bypassing the lap belt guides to create the range of boosters shown in Fig. 3. A new booster seat was used for every adapted booster. Bypassing the guides, by placing the belt above them, was essentially a misuse of the booster. However, it was not the intention to assess the effects of booster seat misuse. Instead, this (and all adaptions) was simply a convenient means of generating different lap belt paths, consistent with paths that might be observed in real, albeit somewhat poorly-designed, booster seats.



No booster
(Seated directly on test bench)

Booster A – Symmetrical guides
(No adaptations)

Booster B – No guides
(Booster A with belt over guides)

Booster C – No guides
(Booster A with guides removed)

Booster D – No guides
(Booster A with forward path)

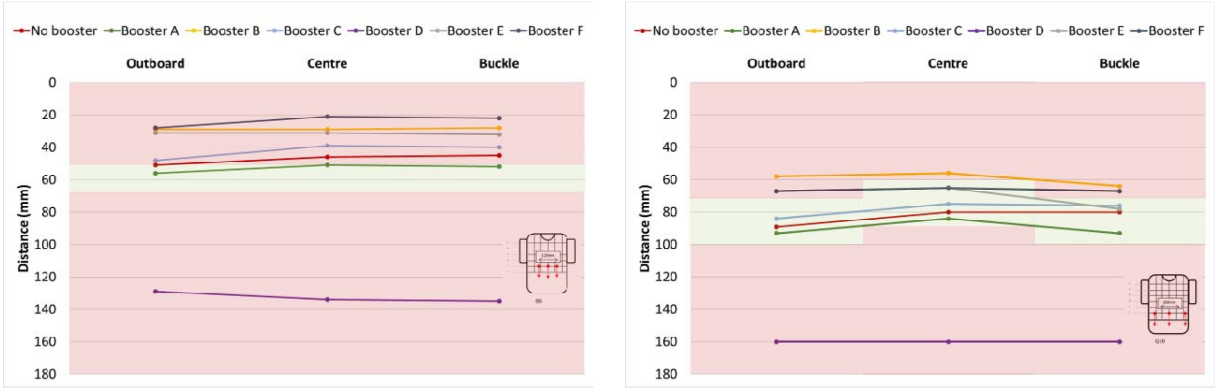
Booster E – Asymmetrical guides
(No adaptations)

Booster F – No guides
(Booster E with belt over guides)

Fig. 3. Booster seats used in the study.

The static position of the lap belt was measured prior to each experiment using a procedure proposed for UN Regulation No. 129, but not implemented to-date (UN Informal Document CRS-58-04e "Belt Path Assessment Text"). In this procedure, the position of the seat belt is measured relative to reference points on the Q-series grid suit. This is measured in three places; in the centre and at a specified distance to the left and right of the centre. The procedure also proposes lap belt position criteria, comprising a minimum and maximum distance from each reference point.

Figure 4 shows static lap belt measurements made prior to each dynamic test, overlaid with the position criteria in the proposed procedure (the green area denotes the acceptable position). A range of different static lap belt paths were generated with the two dummies. Most paths fell outside the acceptable band with the Q6 dummy, but there was a more even spread with the Q10. For the purposes of this study, the lap belt fit of the booster was rated good if all three measurement points fell within the acceptable limits (green area). It was rated poor if any one of the measurements fell outside the limits (red area). These outcomes were summarised in Table I.



Q6 Q10

Fig. 4. Static measurements of lap belt fit for each booster used in the study.

Kinematic Assessment

The kinematic motion of the dummies was recorded using two high-speed video cameras: one positioned at 90° to the direction of travel of the sled; and another positioned to record the interaction between the dummy and the seat belt. A primarily qualitative assessment of the presence of submarining and abdomen loading was made from both camera views, supplemented with quantitative kinematic measures of the dummy excursion. This was used as a basis for analysing the measurement outputs from the APTS and ASIS load cells. A purely quantitative assessment would have been preferable (to avoid subjectivity); however, there is no agreed metric for the Q-Series, beyond the APTS measurements. If another robust metric was available, there would arguably be no need for either the APTS or the ASIS load cells.

The difference between the knee and head excursion (i.e. *knee-head* excursion) was used to quantify the dummy kinematics and belt interaction and hence supplement the qualitative assessment. This was calculated by subtracting the peak forward head excursion measured at the leading edge of the head from the peak forward excursion of the knee joint. In the United States, FMVSS 213 specifies head and knee excursion independently. However, the relationship between the two is potentially more effective for characterising the interaction between a child dummy and the seat belt, with or without a booster. Reference [21] concluded that larger values of knee-head excursion suggest poor restraint of the pelvis, with the potential for submarining. Specifically, knee-head excursions of 200 mm and greater were associated with submarining kinematics. Furthermore, since values approaching 200 mm were thought to have *submarining tendencies*, only values of less than 150 mm were deemed to have *desirable kinematics*. As this previous study used a different child dummy (Hybrid III 6YO) and a different regulatory environment (FMVSS 213), their findings could be used only as a guide in characterising the belt interaction of the Q-Series dummies in the UN Regulation No. 129 environment.

Peak torso angle has also been proposed as an objective measure of belt interaction. Peak angles that are slightly forward of the vertical (i.e. -10° to -20°) are associated with good kinematics, whereas positive values suggest submarining [22]. However, this metric is typically determined using angular rate sensors installed in the dummy spine and pelvis. The Q-Series is not routinely equipped with such sensors, and while film analysis can also be used [23], torso angle could not be determined accurately in our tests because the booster seats obscured the shoulder and hip of the dummy. Torso angle was therefore considered only as an input to the qualitative assessment of the dummy kinematics, and was based on the visible part of the torso only.

III. RESULTS

Lap Belt Interaction with the Pelvis

Table II summarises the kinematic measures and video observations in each test condition for both the Q6 and the Q10 dummies. The kinematic assessment was deemed to be favourable, borderline or unfavourable according to our observations of the peak torso angle and the position of the lap belt throughout the impact event. The knee-head excursion value supplemented this assessment, but could not be used solely as a quantitative measure as no limit values are available for the Q-Series dummies and the UN Regulation No. 129 environment.

Figure 5 shows the interaction between the Q6 dummy and the seat belt around the time of peak pelvic displacement in each booster seat. The bulges visible at the top of the dummy's legs were likely to be part of the hip liner *popping out* from the gap between the legs and pelvis. Typically, the hip liner had returned to its natural position by the time the dummy came to rest.

Favourable kinematic patterns were observed in the experiment with no booster and in Booster A (with symmetrical guides). Both displayed an upright dummy torso, with the lowest knee-head excursion values. More importantly, the lap belt remained on the pelvis throughout the impact. The belt adopted a relatively shallow angle during the test with no booster, and was visibly high on the pelvis, but there was no indication of submarining. Booster A was the only seat with good static belt fit with the Q6.

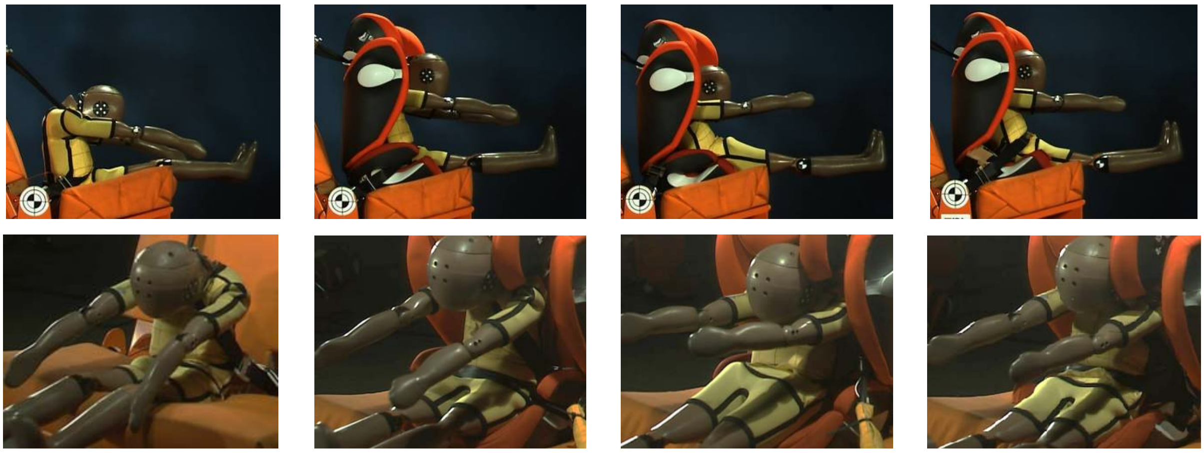
Less favourable, somewhat borderline kinematics were observed in Booster C. The dummy displayed greater knee-head excursion in this seat, with the torso appearing reclined (because it was held back by the diagonal belt), but the belt remained on the pelvis throughout. Unfavourable kinematic patterns with submarining tendencies were observed in the remaining experiments. All displayed high knee-head excursion with a reclined torso. The lap belt moved off the pelvis and loaded the abdomen in Booster B and in Booster D. The belt probably also loaded the abdomen in Booster E and Booster F. However, this could not be observed directly because the dummy's suit and/or abdomen obscured the belt over the critical period.

TABLE II

SUMMARY OF RESULTS (KINEMATIC MEASURES)

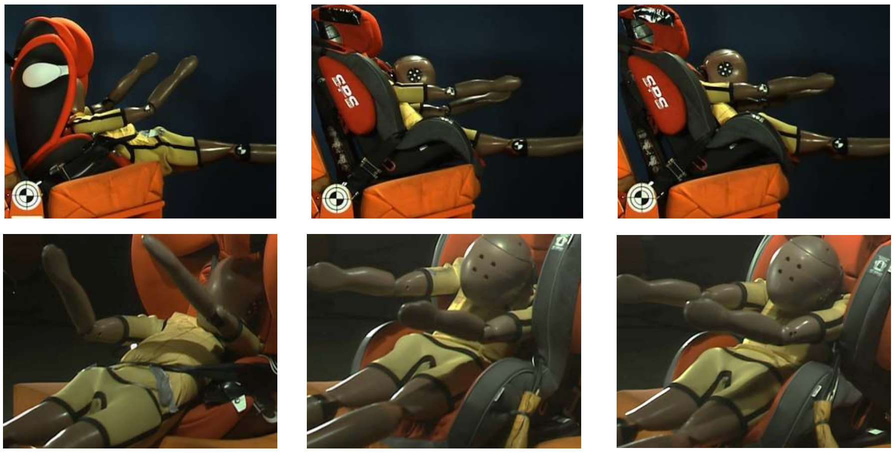
Booster	Dummy	Lap belt fit	Peak torso angle	Excursion (mm) Head	Knee	Knee-head	Kinematic assessment
No booster	Q6	Poor	Upright	328	458	130	Favourable
Booster A	Q6	Good	Upright	408	496	88	Favourable
Booster B	Q6	Poor	Reclined	353	615	262	Unfavourable
Booster C	Q6	Poor	Reclined	353	552	199	Borderline
Booster D	Q6	Poor	Reclined	303	770	467	Unfavourable
Booster E	Q6	Poor	Reclined	359	651	292	Unfavourable
Booster F	Q6	Poor	Reclined	383	703	320	Unfavourable
No booster	Q10	Good	Upright	342	582	240	Favourable
Booster A	Q10	Good	Upright	392	648	256	Favourable
Booster B	Q10	Poor	Reclined	347	755	408	Unfavourable
Booster C	Q10	Good	Upright	371	628	257	Favourable
Booster D	Q10	Poor	Reclined	360	772	412	Unfavourable
Booster E	Q10	Poor	Reclined	390	683	293	Favourable
Booster F	Q10	Poor	Reclined	412	743	331	Unfavourable

No booster **Booster A** **Booster B** **Booster C**



Favourable kinematics: No submarining **Favourable kinematics: No submarining** **Unfavourable kinematics: Probable submarining** **Borderline kinematics: No submarining**

Booster D **Booster E** **Booster F**

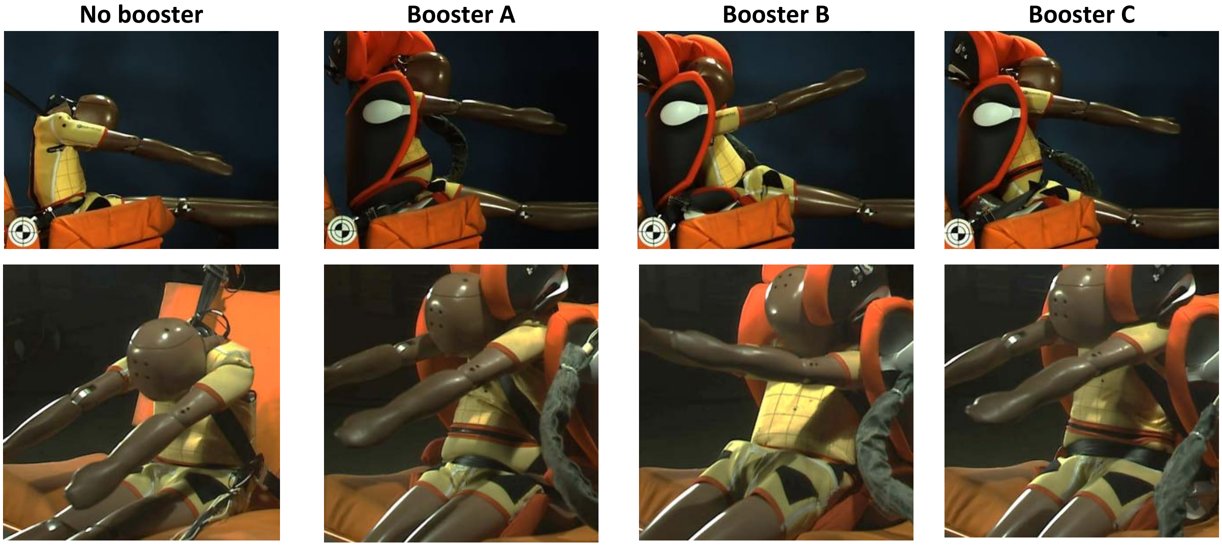


Unfavourable kinematics: Probable submarining **Unfavourable kinematics: Probable submarining** **Unfavourable kinematics: Probable submarining**

Fig.5: Q6 dummy kinematics and belt interaction at or close to peak excursion.

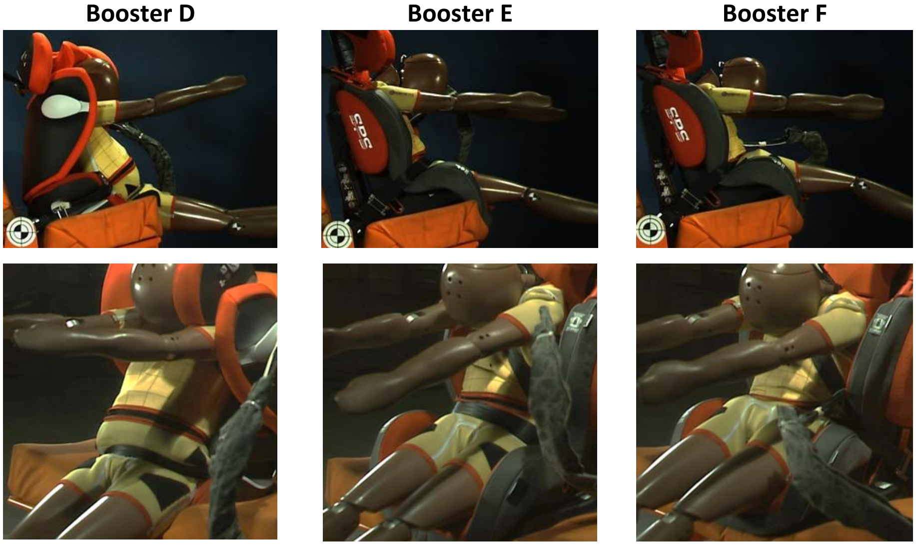
Figure 6 shows the interaction between the Q10 dummy and the seat belt. Favourable kinematic patterns were observed in the experiment with no booster and in Boosters A and C. All displayed an upright dummy torso at peak excursion, with the lowest knee-head excursion. Further, the lap belt remained on the pelvis throughout the impact. These seats displayed a good initial static belt path, which appears to have carried through to the dynamic performance. Borderline kinematics were observed in Booster E, which were characterised by a more reclined torso with greater knee-head excursion. The belt was also visibly high on the pelvis. This booster displayed a poor static belt path, although this resulted from one of the three reference points only.

Unfavourable kinematics were observed in Booster D and in Booster F. High knee-head excursion values were measured (with a reclined torso); nevertheless, the belt remained on the pelvis. Unfavourable kinematics with clear submarining was observed in Booster B. Very high knee-head excursion was observed, with the lap belt moving off the pelvis and loading the abdomen. This booster featured the highest static lap belt path with the Q10.



No booster **Booster A** **Booster B** **Booster C**

Favourable kinematics: No submarining **Favourable kinematics: No submarining** **Unfavourable kinematics: Probable submarining** **Favourable kinematics: No submarining**



Booster D **Booster E** **Booster F**

Unfavourable kinematics: No submarining **Borderline kinematics: No submarining** **Unfavourable kinematics: Possible submarining**

Fig. 6: Q10 dummy kinematics and belt interaction at or close to peak excursion.

Abdominal Pressure Twin Sensors (APTS)

Figure 7 shows the peak pressure in the left and right of the APTS in the Q6 dummy. The lowest pressure was recorded when the lap belt remained on the pelvis. For instance, the experiments with no booster and with Booster A displayed the most favourable kinematics and belt interaction. No abdomen loading was observed and the peak pressures were relatively low with respect to the regulatory threshold (1.0 bar). The belt also remained on the pelvis in Booster C, albeit with less favourable kinematics. Low pressure was recorded in this experiment, and at a similar level to Booster A.

The highest pressures were recorded in experiments with undesirable kinematic patterns. The pressure exceeded the regulatory threshold in Booster B and Booster F. Submarining was observed in Booster B and suspected in Booster F. These booster seats also featured the highest static belt path. The pressure was high, but did not exceed the threshold in the remaining experiments with observed or suspected submarining. In Booster D, the APTS measured the threshold value in the right bladder, which would still constitute a *pass* from a regulatory perspective. However, the dummy very clearly submarined in the experiment. The somewhat limited pressure, given the kinematics, probably occurred because the belt slid up the abdomen rather than penetrating it fully. In Booster E, the pressure fell just below the threshold. The kinematic pattern suggested submarining, but it could not be verified from the video. It is possible that the dummy adopted a reclined (almost supine) posture, but the belt stayed on the pelvis. However, the APTS did measure markedly higher pressure than the clear no submarining tests, which suggests the belt did load the abdomen, just not enough to reach the threshold.

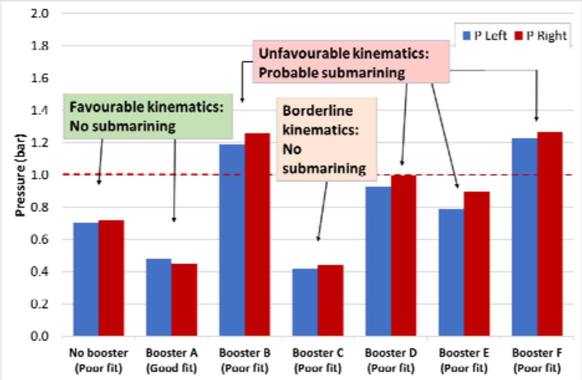


Fig. 7. Peak abdomen pressure - Q6

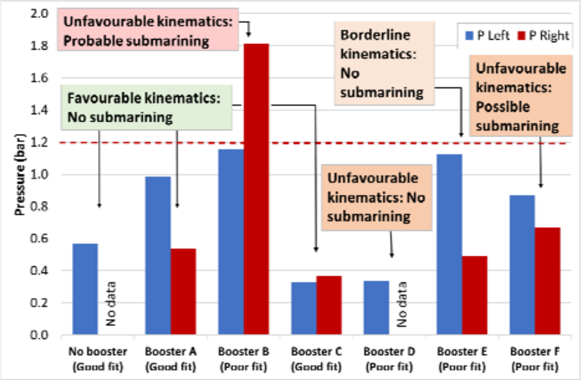


Fig. 8. Peak abdomen pressure – Q10

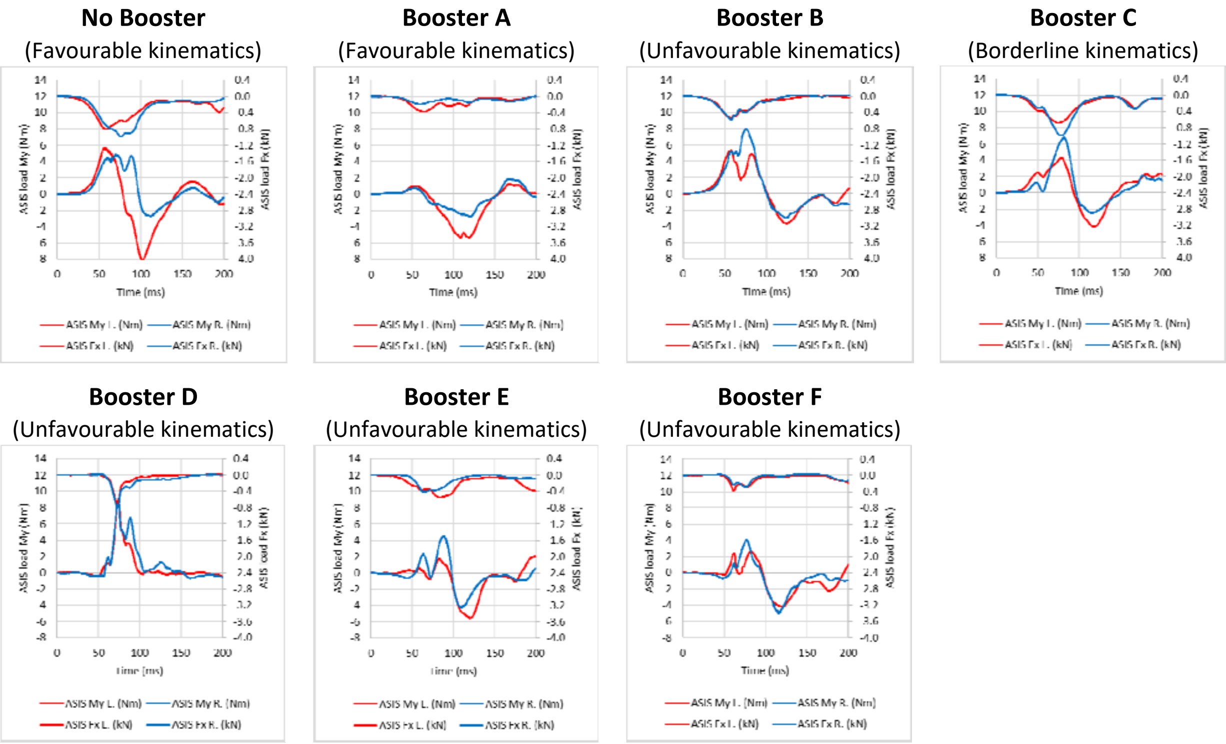
Figure 8 shows the peak pressure with the Q10 dummy. Unfortunately, the right-side, i.e. upper anchorage-side, channel was not available in two tests, due to cable damage, which could not be repaired during the experiment window. Low pressure tended to be recorded when the lap belt remained on the pelvis (notwithstanding the missing data). For instance, the experiments with no booster and Booster C both displayed favourable kinematics and belt interaction and relatively low pressure against the regulatory threshold (1.2 bar). However, Booster A also displayed favourable kinematics with no submarining tendencies, but the pressure in the left bladder was close to the regulatory threshold. This was surprising because Booster A displayed the lowest (static and dynamic) belt path. The lap belt was low on the pelvis and guided by the booster throughout the impact. Given the loading was focussed on the left side, it is possible that the diagonal belt played a role; however, the diagonal belt also appeared to have moved above the abdomen during the period of loading.

Low to moderate pressure was recorded in booster seats with unfavourable kinematics, but no submarining. For instance, Booster D displayed very poor control of the pelvis, but the belt remained engaged and very low pressure was measured in the left bladder (the right channel was lost). Booster F measured moderate pressure, but the peak value was less than Booster E. Booster F was essentially a misused version of Booster E (the belt was placed above the guide) and hence it would not be expected to display better abdominal performance. Both peaks occurred on the left-side, which further suggests the involvement of the diagonal belt in such a way that sub-optimal diagonal belt paths can lead to reduced abdomen pressure. That said, the highest pressure was recorded in the experiment with the unfavourable kinematics and clear submarining. The lap belt moved off the pelvis in Booster B and the peak pressure exceeded the regulatory threshold for the Q10.

Anterior-Superior Iliac Spine (ASIS) Load Cells

Figure 9 shows the outputs from the ASIS load cells in the Q6 dummy. Each chart comprises left- (red) and right-side (blue) force (Fx) and moment (My). A range of ASIS force levels were generated. The lowest force against the ASIS was measured in Booster A. The structure of the booster and its belt guide seems to have limited the transfer of belt forces to the ASIS. The highest force was measured with no booster and in Boosters C and D. Booster D also experienced a rapid drop-off in the force. The dummy very clearly submarined and hence this response may be indicative of the belt moving off and no longer loading the ASIS. However, the dummy was also observed to have submarined in Booster B, and was suspected to in other seats, but no similar force drop-offs or any other significant trends were observed in the ASIS force.

The ASIS moments tended to display a period of positive moment during the loading phase of the impact, followed by a period of negative moment in the unloading phase. When the belt interaction was very favourable, as in the case of Booster A, the positive moment in the loading phase was relatively low (because the belt was low on the pelvis, just above the neutral axis of the load cell). In other seats, the initial period of positive moment tended to be higher, probably reflecting the higher position of the belt above the neutral axis of the sensor. However, Booster D displayed a somewhat difference response, characterised by a period of high positive moment, which fell away and remained at zero for the duration of the unloading phase. This seems indicative of submarining, whereby a high moment is generated by the belt at the top of the ASIS, before it falls to zero after the belt moves into the abdomen. Unfortunately, this trend was not apparent in other tests in which submarining was observed or suspected. In fact, all remaining tests with submarining tendencies displayed periods of negative moment in the unloading phase. It was unclear how this loading was generated since the videos tended to show the belt being some distance from the sensor position in this period.


No Booster
(Favourable kinematics)

Booster A
(Favourable kinematics)

Booster B
(Unfavourable kinematics)

Booster C
(Borderline kinematics)

Booster D
(Unfavourable kinematics)

Booster E
(Unfavourable kinematics)

Booster F
(Unfavourable kinematics)

Fig.9. ASIS force and moment time histories – Q6.

Figure 10 shows the ASIS force against the moment in selected seats. The booster with the most favourable belt interaction (Booster A) displayed a response that was (almost) exclusively outside the *red area*. In contrast, the two boosters in which submarining was observed visually (Booster B and Booster D) displayed responses that were markedly inside the red area. However, the trends in the remaining seats were less clear.

Booster A
(Favourable kinematics)

Booster B
(Unfavourable kinematics)

Booster D
(Unfavourable kinematics)

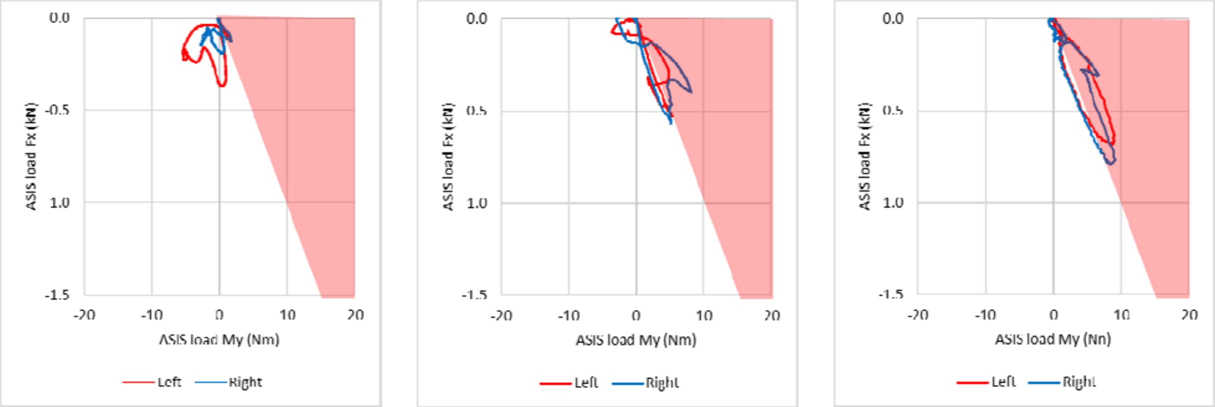
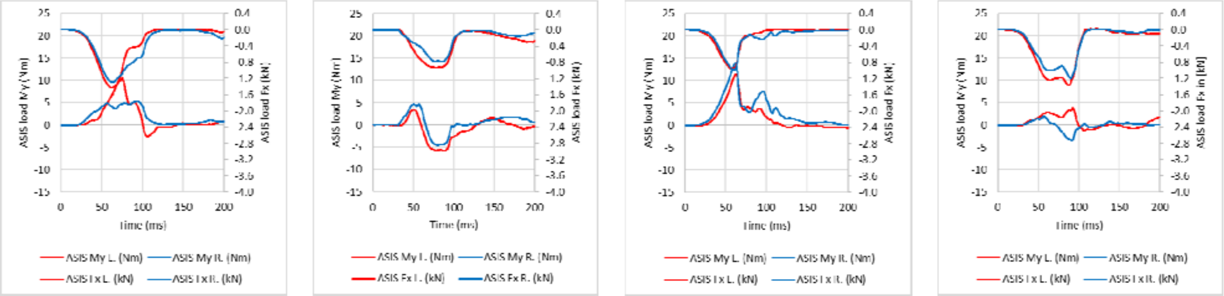


Fig. 10. ASIS force against moment in selected experiments – Q6.

Figure 11 shows the outputs from the ASIS load cells in the Q10 dummy, comprising left- (blue) and right-side (red) force (Fx) and moment (My). The ASIS force level tended to be reasonably consistent across the seats with no significant trends in the shape and magnitude of the responses. Nevertheless, the lowest force against the ASIS was measured in Booster A. Once again, this booster seems to have limited the transfer of belt forces to the ASIS, although the difference was more marginal than in the Q6 tests.

The ASIS moment displayed a range of responses. When the belt interaction was most favourable (i.e. Booster A), the ASIS displayed a period of (low) positive moment during the loading phase of the impact, followed by a period of negative moment in the loading and unloading phase. This was consistent with the responses observed with the Q6 dummy. Experiments with unfavourable kinematics and belt interaction tended to display periods of predominantly high positive moment only. For example, the lap part of the belt was observed to move off the ASIS in Booster B. This seat displayed a short duration initial peak in the positive moment, which fell away very rapidly at the same time the force appeared to drop off. This seems to reflect and confirm the submarining that was observed.

No booster (Favourable kinematics) **Booster A** (Favourable kinematics) **Booster B** (Unfavourable kinematics) **Booster C** (Favourable kinematics)



Booster D (Unfavourable kinematics) **Booster E** (Borderline kinematics) **Booster F** (Unfavourable kinematics)

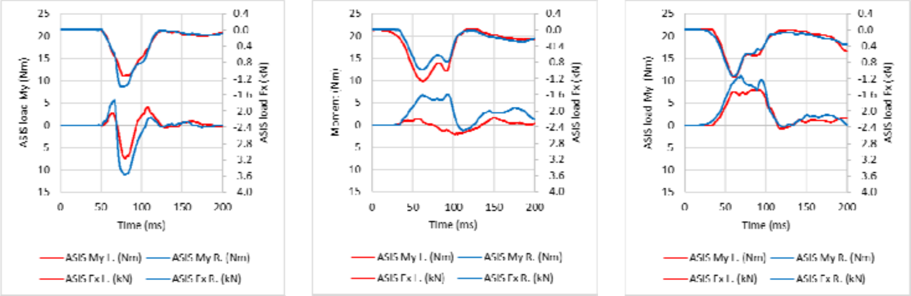
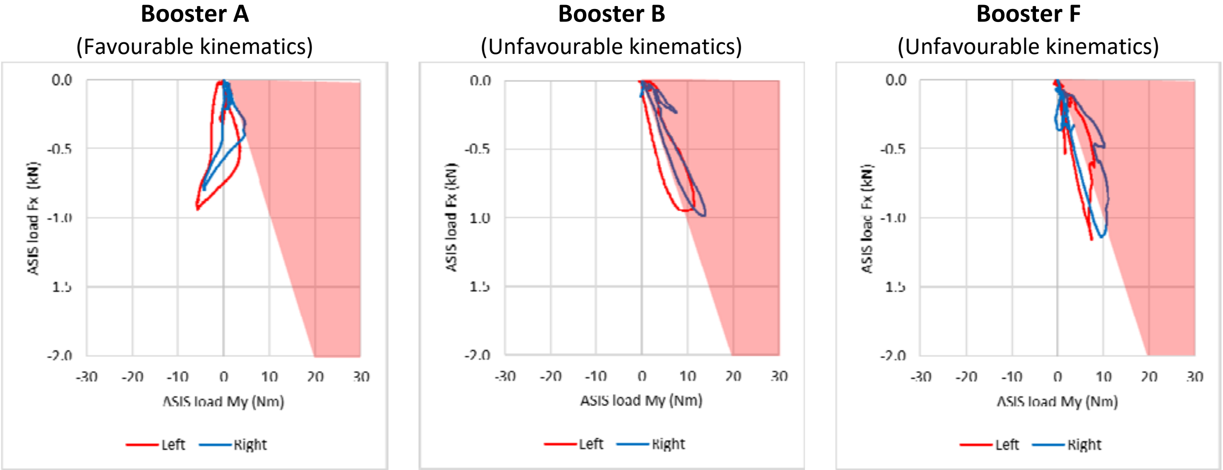


Fig. 11. ASIS force and moment time histories – Q10.

Figure 12 shows the ASIS force against the moment in selected seats. The booster with the most favourable belt interaction (Booster A) displayed a response that was mostly outside the *red area*. In contrast, the booster in which submarining was observed visually (Booster B) and suspected (Booster F) displayed responses that were markedly inside the red area. However, the trends in remaining seats were less clear.


Booster A
(Favourable kinematics)

Booster B
(Unfavourable kinematics)

Booster F
(Unfavourable kinematics)

Fig. 12. ASIS force against moment in selected experiments – Q10.

IV. DISCUSSION

The booster seats used in this study generated a spread of favourable and unfavourable dummy kinematic patterns and belt interactions, with some displaying submarining tendencies. This provided a range of conditions under which to compare the APTS and ASIS load cells and their capacity to distinguish differences between the level of abdomen protection afforded by booster seats. These experiments were, to our knowledge, the first that attempted such a comparison for the Q-Series dummies.

The APTS detected very clear instances of submarining in both the Q6 and Q10. The belt was confirmed to have moved off the pelvis (in the video) and the abdomen pressure exceeded the regulatory threshold for each dummy. The APTS were less capable of discriminating unfavourable kinematics and belt interactions in which submarining was suspected or was very close. These kinematic patterns were clearly *unfavourable* because the dummy displayed a reclined torso at peak excursion with substantial pelvic displacement (i.e. high knee-head excursion). However, the position of the belt was obscured by the dummy's suit and/or abdomen. In some cases, submarining was strongly suspected, but could not be verified from the video. In others, the belt seemed to have stayed on the pelvis, albeit in a very high position. Although the Q6 tended to measure relatively high pressures during these unfavourable kinematics, they fell below the regulatory threshold. The trends were less clear with the Q10, which measured a spread of pressures.

The APTS recognised favourable kinematics and belt interactions, but this was also somewhat dependent on the dummy. For example, relatively low pressure (40 to 60% of the threshold) was measured in the Q6 when the belt remained on the pelvis with good overall kinematics. In contrast, the Q10 sometimes measured relatively high pressure (over 80% of the threshold) with the belt low on the pelvis. This was particularly noticeable in the booster with the most desirable features – a low static and dynamic belt path and guidance on both sides. The diagonal belt seemed to be responsible for this loading, which was also the conclusion following similar observations with a *good* booster in [16]. Although the diagonal belt can undoubtedly load the abdomen in real children, its contribution to injury risk does not appear to have been quantified. Nevertheless, the implication is that boosters that position and control the seat belt can generate much higher abdomen pressure in the Q10 than boosters with less favourable belt interactions. This seems undesirable from the point of view of encouraging good booster design for this size child.

The ASIS load cells also detected the most unfavourable kinematics and belt interactions with clear submarining. In these experiments, the response displayed a high positive moment that fell away very rapidly and remained at zero throughout the rest of the impact. This implied the belt had moved off the ASIS and stayed in the abdomen with no further pelvic interaction. A proposed threshold line on the ASIS force against moment plot was also exceeded for extended periods, further indicating unfavourable interactions. The ASIS load cells displayed a somewhat inconclusive response to instances of unfavourable kinematics and belt interaction in which submarining was suspected, but not verified. These typically comprised periods of high, sometimes oscillatory, positive moment, followed by periods of negative moment spanning both the loading and unloading phases. This suggests the belt was engaging the pelvis throughout the impact and was in a relatively low position, below the neutral axis of the sensor, in the later phase. However, the video did not always show the belt in this position, which implies the negative moment was generated by some other mechanism. Further investigation is needed to determine what was causing the sensor output in this period. One option might be to develop the ASIS load cells further, with the introduction of an extra channel for the vertical force (Fz) component. This would provide a full picture of the x-z plane loading at the ASIS and may improve the detection of borderline belt interactions.

The ASIS load cells reflected the most favourable kinematics and belt interactions. The moment tended to display a period of positive moment in the loading phase, followed by a period of negative moment later in the loading phase and into the unloading phase. The ASIS load cell appeared to be particularly sensitive to the booster with optimised features (low belt path, guides on both sides) particularly in the Q6. The initial positive moment was small, suggesting the belt was low on the ASIS, just above the neutral axis, before moving to a lower position in the later phases. Other boosters, albeit with ultimately favourable kinematics, displayed higher positive moments, indicating the belt was higher on the ASIS during the impact.

In general, both sensors were sensitive to the extremes (good and bad) of the kinematic patterns and belt interactions observed in this study. Very high belt paths with clear submarining were distinguished from low belt paths with no submarining and favourable kinematics. However, both sensors struggled to some extent with everything in between. Several boosters displayed unfavourable kinematic patterns with suspected, but ultimately unverified, submarining. Neither the APTS, nor the ASIS load cells fully discriminated these seats from much more favourable examples. It is possible that the sensors were simply reflecting the dummy behaviour, which was also inconclusive. For instance, if substantial pelvic displacement was observed with a very reclined torso, but the belt stayed on the top of the ASIS, it is difficult to assess what response the APTS or the ASIS load cells should display. It seems desirable for a sensor (and any performance threshold) to discriminate all unfavourable interactions and encourage product development in an appropriate direction. Nevertheless, if these kinematics and/or interactions, whilst unfavourable, are not necessarily injurious, it might also be reasonable for the sensors not to distinguish them fully. That would rely on the dummy to mimic a human response very closely. However, if a child is more susceptible to submarining when it adopts these unfavourable kinematics, because the pelvis more readily rotates rearwards, the dummy may not capture the risks fully [13].

A key assumption of the study was that the dummy was displaying realistic kinematic patterns and submarining (or not) under conditions in which the same would be expected from a child. This aspect of the Q-Series has been researched extensively since it was first introduced [12]. Although the seat belt can become trapped in the gap between the legs and pelvis, the hip liners were thought to have solved this problem and improved the interaction between the dummy and belt [14]. The dummy submarined several times in our study, but there were also examples of favourable kinematics, in conditions under which less favourable kinematics were expected: for example, when the dummies were seated directly on the bench. The Q10 is the largest dummy available in the Q-Series (and in regulatory testing) and occupies the border between child restraint and adult seat belt use. A child of the same stature as the Q10 (1,443 mm) can legally use the three-point seat belt in around half of EU Member States. It seems appropriate, therefore, for this dummy to display adequate kinematics and belt interactions without a booster seat. However, the Q6 stature (1,173 mm) falls well below the minimum stature for adult seat belt-wearing (1,350 mm). Although a booster seat offers a range of benefits, from a regulatory perspective, it would also be desirable if a booster was needed to ensure favourable belt geometry and interaction (since that is, largely, its main aim). In our experiment, the Q6 displayed favourable kinematics with low pelvic displacement and an upright torso at peak excursion. The lap belt remained on the pelvis throughout, albeit a little higher than the ideal position. Other studies concluded that the belt loaded the abdomen when the Q6 was placed directly on the test bench; however, this was not apparent upon closer inspection since the suit and abdomen obscured the camera view [14]. Similarly, although abdomen loading was suspected in [16], the authors conceded that submarining did not occur fully. In the same study, it was possible to generate submarining with Q6 only when a higher pulse was used and a different seating procedure. Clear evidence of submarining was observed in [24], but the dummy was seated on a US regulatory bench with a static seat belt. On the current evidence, a booster seat is not needed (to provide abdomen protection) at this regulatory test condition. The regulation is essentially assessing that the booster is not detrimental to abdomen protection, rather than enhancing it. State-of-the-art human body modelling might be the best approach to validating the kinematic patterns and belt interaction of the Q6 in this scenario.

This study highlighted the difficulties associated with visual and subjective assessments of dummy-belt interaction and the need for objective measures. However, both sensor-based methods investigated in this study were sensitive only to the extremes of good and poor pelvis restraint. In contrast, the measures used to classify the booster seats (initial, static belt path) and to quantify the dummy kinematics (knee-head excursion) were arguably more effective in distinguishing differences among the seats. For example, favourable kinematic patterns were observed when the initial, static belt path was low on the abdomen. This was characterised by a low knee-head excursion value. Less favourable kinematics and belt interactions were observed when the static belt path was higher on the abdomen. This was characterised by a markedly higher knee-head excursion value. These measures were intended to provide supplementary information for our main investigation of the APTS and ASIS load cells. However, given the inconclusive nature of some of the sensor measurements made in this study, developing either or both measures further might be a pragmatic solution until some of the issues with the test tools can be solved fully.

V. CONCLUSIONS

Both the APTS and the ASIS load cells were sensitive to the extremes of dummy kinematics and belt interactions observed in the experiments. They detected clear cases of submarining in which the belt was observed in the abdomen in videos, as well as the most favourable kinematics and belt interactions (except the APTS in the Q10, where good positioning and control of the lap and diagonal belts led to higher abdomen pressure than boosters that provided less optimum interactions). However, both sensors did not always distinguish borderline situations in which the kinematics and belt interaction were very clearly undesirable, but submarining could not be verified (because the belt was obscured) or did not occur. The initial static belt fit and knee-head excursion seemed better predictors of favourable kinematics than either sensor in these conditions.

The ASIS load cells offered complimentary information to the APTS. The APTS detect loading to the abdomen above the ASIS, whereas the ASIS load cells provide information about the interaction of the pelvis with the belt, in a region not covered by APTS. However, although they were complimentary in terms of the data they provided, the value derived from the ASIS load cells was ultimately duplicative in our tests. That said, the response of the ASIS load cells needs to be better understood in a larger programme of work. It remains reasonable that the sensors could form a basis to develop performance criteria for ASIS loads that encourage booster designs that keep the belt low on the pelvis.

VI. ACKNOWLEDGEMENT

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