Sensitivity of the Q-Series Abdominal Pressure Twin Sensors to Loading Type and Position in Dynamic Restraint System Loading Tests

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Abstract The Abdominal Pressure Twin Sensors (APTS) measure restraint loading to the abdomen of the Q-Series dummies. The sensors were found not to influence the response of the abdomen in moderate-rate belt compression tests using a material testing machine. The APTS were also found to be sensitive to restraint loading type and position. A material testing machine provides a very controlled means of loading the abdomen to characterise its response. However, it may not replicate the effects of loading typical of a dynamic collision event. This paper describes a series of restraint loading tests in which the test device provided a high-rate dynamic, yet controlled, restraint system input to the abdomen.

The APTS increased the stiffness of the Q3 abdomen in these tests with dynamic restraint loading. The Q3 abdomen and the APTS were sensitive to the type and location of the restraint loads. Engaging the pelvis of the dummy is likely to reduce deflection and pressure for a given force for any restraint type. However, the APTS do not descend fully into the pelvis and hence it may be possible to load the abdomen in front of the pelvis in a region not covered by the sensors.

Keywords Abdomen, Child, Dummy, Q-Series, Sensor.

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]. The lap part of a seat belt is intended to pass over the top of the occupant's thighs. The anterior superior iliac spines of the pelvis serve as an anchor point for the belt and help to maintain its position during a collision. 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]. Non-integral child restraint systems (i.e. 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 also observed in these child restraints systems (CRS) [7-8].

United Nations (UN) Regulation No. 129 (on Enhanced Child Restraint Systems) came into force in June 2013. Initially, it applies only to integral ISOFIX CRS, but will eventually include all child restraint types. For instance, it is currently in the process of being amended to enable the type-approval of booster seats. The regulation specifies the Q-Series family of child dummies for use in front, side and rear impact tests. The Q-Series was developed with superior biofidelity and injury assessment capabilities, as compared with the P-Series (its predecessor in child restraint approval legislation) [9]. However, until recently it did not feature any means of detecting the presence or magnitude of abdominal loading by a restraint system.

The Abdominal Pressure Twin Sensors (APTS) were developed across several European Union collaborative research projects [10]. They measure restraint system loading to the abdomen of the Q-Series in front impact tests, thereby fulfilling the need for instrumentation in this body region of the dummy. The sensors have been evaluated extensively and a pressure-based injury criterion developed from accident reconstruction [11]. The

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APTS were recently introduced in UN Regulation No. 129, and are also used in consumer testing of CRS carried out by European Test Centre.

Beillas *et al*. found that the APTS do not influence the response of the abdomen in moderate-rate belt compression tests using a material testing machine [12]. In the same tests, the APTS were also found to be sensitive to restraint loading type and position [12-13]. Appropriate sensitivity is likely to be desirable in discriminating differences in protection between CRS. Understanding this sensitivity is likely to be beneficial to restraint designers. A material testing machine provides a very controlled means of loading the abdomen in order to characterise its response. However, it may not replicate the effects of loading typical of a dynamic collision event. This paper describes a series of restraint loading tests in which the test device provided a high-rate dynamic, yet controlled, restraint system input to the abdomen. The aim was to bridge the gap between the previously reported moderate-rate tests and full sled tests in understanding the sensitivity of the APTS to loading type and position.

II. METHODS

Abdomen testing approaches

Beillas *et al*. [12-13] used a material testing machine and a set of conditions that were intended to replicate the biofidelity assessment of the Q-Series undertaken by the European Enhanced Vehicle Safety Committee (EEVC) [9]. These comprise a force-deflection response corridor for the dummies in belt loading tests. These methods and conditions were in turn derived from scaled porcine corridors presented by Rouhana *et al*. [14]. More recently, Kent *et al*. developed a new porcine model for a 6yo abdomen and presented its biomechanical response under dynamic belt loading [15]. The model was validated against quasi-static, non-injurious child volunteer data published by Chamouard *et al*. [16] and against the distribution of injuries sustained by children in the field. The analysis was further expanded with two paediatric (PMHS) tests [17].

The methods developed by Kent *et al*. were chosen as a basis for this study as they appeared to offer the potential for accurate and consistent loading to the APTS in a way that was also representative of a real collision event. It was not the aim of this study to re-evaluate the biofidelity of the Q-Series abdomen. Instead, the focus was solely on investigating the APTS and their sensitivities in controlled, but dynamic, restraint loading conditions.

Test equipment and procedure

The test set-up is shown in Fig. 1. The test fixture provided two-point belt loading on the anterior abdomen of the dummy using a 5 cm-wide belt. The dummy was placed supine on the table and the belt was positioned across the anterior abdomen. The two ends of the seat belt passed through the table over low friction supports and were attached to a horizontal loading bar. This bar/rod was pulled down by another length of the same seat-belt material, around a pulley, and connected to the back of a miniature (30 kg) bungee-powered sled. The movement of the loading bar was activated by dynamic movement of the sled. The tension force at each end of the belt passing over the dummy was measured with a seat-belt load cell before connection to the loading bar. These channels were averaged to provide the belt force. Movement of the belt was measured with linear variable differential transformers (LVDTs) mounted to a frame above the dummy. The force measurements from three load cells under the table supporting the dummy were combined to provide a total reaction force.

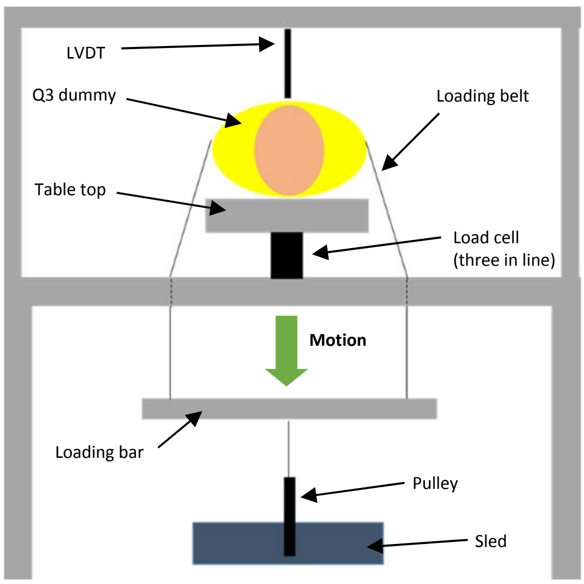


Fig. 1. Table-top test fixture.

The test matrix is shown in Table I. The matrix comprises 13 tests. In fact, each test was repeated once, to make a total of 26 tests completed. High-speed digital video was recorded for each test, at a frequency of 1,000 frames per second. All sensor channels were sampled recorded at 20 kHz and processed according to ISO 6487. Three variable test conditions were examined: loading type, location and velocity. The abdomen was loaded by seat-belt webbing directly or via an impact shield. In each case, there were three loading positions. In the middle position, the centre of the belt or shield was aligned with the transverse centre of the abdomen. In the lowest position, the belt or shield was moved approximately 40 mm down the abdomen such that it engaged fully with the pelvis. In the highest position, the belt or shield was moved approximately 40 mm up the abdomen such that it aligned with the top of the abdomen and partially engaged the ribs (particularly in the case of the shield). Each loading position was investigated with two loading velocities. These were chosen to generate abdomen loading in a range that was consistent with that observed in regulatory and consumer testing. At the first level, the sled was given an initial velocity of 3.0 m/s, which produced approximately 50 mm of abdomen compression in 40 ms; with an instantaneous peak velocity of approximately 3 m/s. At the second level, the sled was given an initial velocity of 4.3 m/s, which produced approximately 70 mm of abdomen compression in 45 ms, with an instantaneous peak velocity of approximately 4.6 m/s.

TABLE I
TEST MATRIX

APTS	Loading type	Loading position	Loading velocity (m/s)
Without APTS	Seat belt	Middle	3.0
With APTS	Seat belt	Low	3.0
			4.6
		Middle	3.0
			4.6
		High	3.0
			4.6
	Shield	Low	3.0
			4.6
		Middle	3.0
			4.6
		High	3.0
			4.6

Dummy preparation

The production version of the Q3 APTS was used in this study (see Fig. 2). This measures pressure in two cylindrical, fluid-filled bladders that are inserted vertically in the abdomen. Each bladder is closed by an aluminium cap that includes a pressure cell. The bladders are inserted ‘cap down’ in a specially moulded abdomen. The pressure measurements were averaged in this study since the test equipment produced symmetrical left-right loading to the abdomen. The dummy was also instrumented to measure chest deflection. The standard dummy neoprene suit was used in all tests. The suit is 5 mm thick and although it obscured the interaction between the restraint and the abdomen, it is an integral part of the dummy. It is worn in all testing and when the dummy is certified. The suit was also worn when the biofidelity of the dummy was assessed [9]. A dummy accessory (known as a hip liner) is used with the Q-Series in regulatory tests to prevent the lap part of the seat belt from becoming trapped in the gap between the legs and pelvis of the Q-Series dummy. However, the hip liner was not used in these restraint loading tests because it was designed to fit into a seated dummy.

Fig. 2. Q3 abdomen fitted with APTS.

III. RESULTS

Effect of APTS on abdomen response

Fig. 3 compares the force-deflection response of the Q3 dummy when equipped with APTS ("with APTS") with its response with a standard abdomen ("without APTS"). The chart on the left of the Figure uses the belt force, whereas the chart on the right uses the reaction force. Belt loading was applied to the middle of the abdomen in these tests to minimise the influence of the chest or pelvic structures. These tests were carried with a loading velocity of 3.0 m/s. The figure shows that the dummy displayed a stiffer response with an abdomen that was equipped with APTS. These findings were consistent between the seat-belt force and the reaction force. The test with APTS generated abdominal deflection of 52 mm, which corresponded to 34% of the total abdominal depth. This generated a peak belt force of 2.81 kN and a peak reaction force of 2.34 kN. In contrast, the test without APTS generated abdominal deflection of 61 mm (40% of total depth), with a peak belt force of 2.51 kN and peak reaction force of 2.12 kN. The reaction force was lower than the belt force at peak deflection because other factors (e.g. belt elongation) mitigated the transmission of the force to the reaction plate.

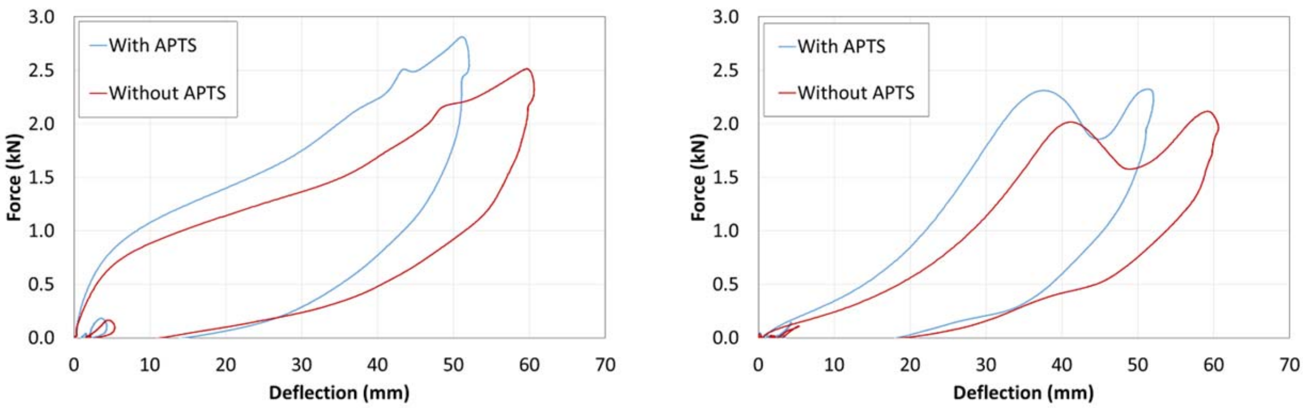
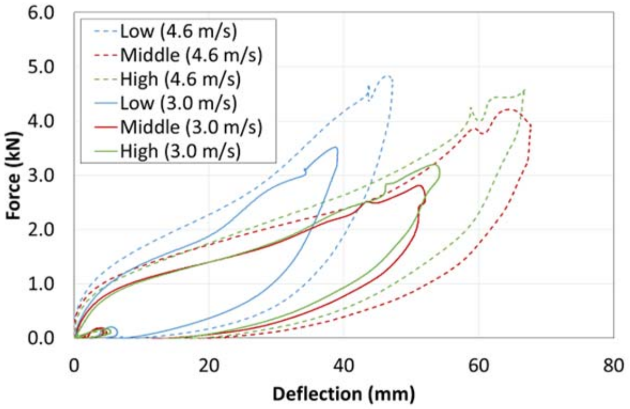


Fig. 3. Seat-belt (left) and reaction (right) force vs. deflection with and without APTS installed in the Q3.

Effect of belt position on abdomen response

Fig. 4 shows the force-deflection response when belt loads were applied to different segments of the abdomen (i.e. low, middle and high) of the Q3 dummy. The responses are coloured by loading position with the line style denoting the loading velocity. The chart on the left of the figure uses the belt force, whereas the chart on the right uses the reaction force. The abdomen was equipped with APTS in these tests. The stiffest response was observed in the lowest loading position, regardless of velocity. In this position, the belt engaged with the pelvis of the dummy (see Fig. 7). The middle and high loading positions were relatively similar in stiffness (to each other), although the high position displayed a slightly higher force at peak deflection. This was probably a result of belt interaction with the rib cage. The centre portion of the belt passed over the top of the abdomen in the high loading position and came into contact with the rib cage as it wrapped around the dummy.

The belt force-deflection response (Fig. 4, left) displayed some evidence of rate dependency up to the first 5 to 10 mm of deflection. Beyond this level, however, the gradient (i.e. force per unit deflection) at each velocity was relatively consistent for each loading position. Inertial effects may have played a role in the response in this early loading phase, potentially accounting for the different rate response. Overall the features controlling most of the abdomen's resistance to compression provided a similar force-deflection response, within the ranges tested in this study. It should be noted that this period of apparent rate dependency was not observed in the reaction-force-deflection response (Fig. 4, right).



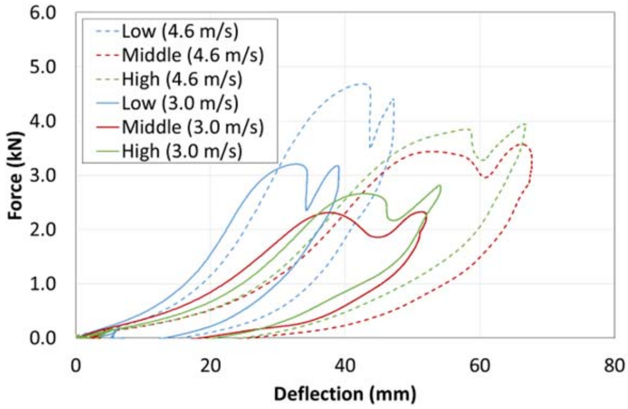


Fig. 4. Effect of belt position: belt (left) and reaction (right) force vs. deflection.

Fig. 5 shows the abdomen pressure vs. deflection response when belt loads were applied in different positions of the abdomen. Negligible pressure was measured with the belt in the lowest position, at both test velocities. As noted above, the belt engaged with the pelvis in this loading position; nevertheless, 39 mm and 47 mm of peak deflection were observed in the 3.0 m/s and 4.6 m/s tests respectively. In each case, this corresponded to around 70% of the deflection observed in the middle position. However, this generated a peak abdominal pressure of around only 20% of the middle position. This suggests a lack of sensitivity in the pressure response of the Q3 dummy in the pelvic region of the lower abdomen.

The middle and high loading positions generated very similar responses. That said, in the 3.0 m/s test, greater deflection was observed in the high loading position (compared with the middle position), whereas the opposite trend was observed in the 4.6 m/s test. Although these differences in deflection were rather small, it appeared that interaction with the rib cage became more significant at the higher speed. Overall, the rate of loading did not affect the shape of the responses greatly across all loading positions, but the peak pressure and deflection increased, as expected.

Fig. 6 shows the abdomen pressure vs. belt force response. For a given force, the highest pressure was measured in the middle of the abdomen, followed by the high position and then the low position. This was consistent with trends observed in Fig. 4 and Fig. 5 and further highlights the influence of belt engagement with the pelvis (low position) and rib cage (high position). Once again, the rate of loading did not affect the shape of the response greatly.

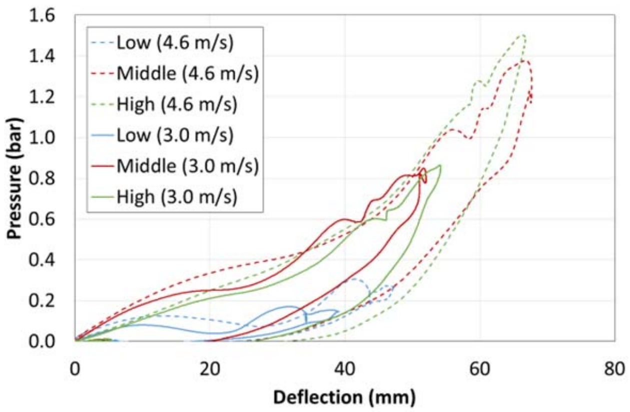


Fig. 5. Effect of belt position – abdomen pressure vs. deflection.

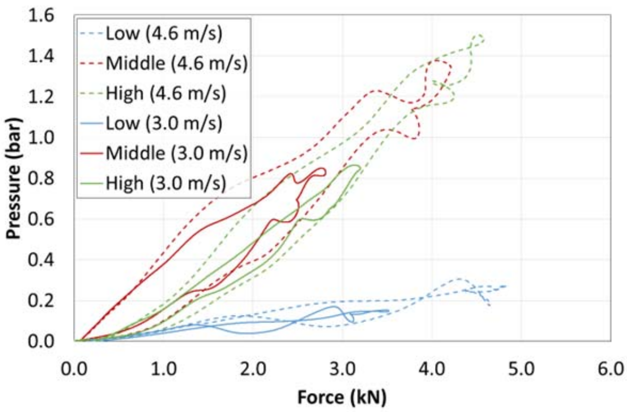


Fig. 6. Effect of belt position – abdomen pressure vs. belt force.

Low Middle High

Fig. 7. Belt interaction with the Q3 abdomen in each loading position (3.0 m/s tests).

Effect of shield position on abdomen response

Fig. 8 shows the force-deflection response of the Q3 when belt loads were applied with an impact shield in different segments of the abdomen (i.e. low, middle and high). The chart on the left of the figure uses the belt force, whereas the chart on the right uses the reaction force. Deflection was measured on the surface of the impact shield (see Fig. 11). The size of the shield meant that it may have engaged with the rib cage and/or the pelvis as well as the abdomen in some loading positions. The deflection measurement therefore represented the torso deflection, rather than the abdomen deflection by itself. The abdomen was equipped with APTS in these tests.

The trends observed in the force-deflection response with a shield depended somewhat on the loading velocity. At the lower velocity, 3.0 m/s, there was some evidence of a stiffer response in the lower loading position, but overall, the response was reasonably similar to that of the middle loading position. The greatest deflection for a given force was observed in the highest loading position; however, the gradient (i.e. force per unit deflection) appeared reasonably similar to that of the low and middle positions. When considering the belt force, the main differences between the loading positions at this velocity seemed to occur over the first 5 mm of deflection. In contrast, at the higher loading velocity, 4.6 m/s, there was stronger evidence for a stiffer response in the lower loading position. This position displayed a distinct response from the middle and high positions, which were reasonably similar (to each other). When the shield was in the lowest position, it engaged more fully with the pelvis from the outset of the loading, compared with higher loading positions. This seemed to have the greatest influence in the higher velocity tests. As the shield was moved further up the torso, engagement with the pelvis reduced, but interaction with the rib cage increased. This seemed to have greatest influence in the lower speed tests.

Once again, the belt-force deflection response displayed some evidence of rate dependency in the early loading phase, up to 5–10 mm. Beyond this, the gradients were consistent, with limited evidence for rate dependency at greater deflection levels.

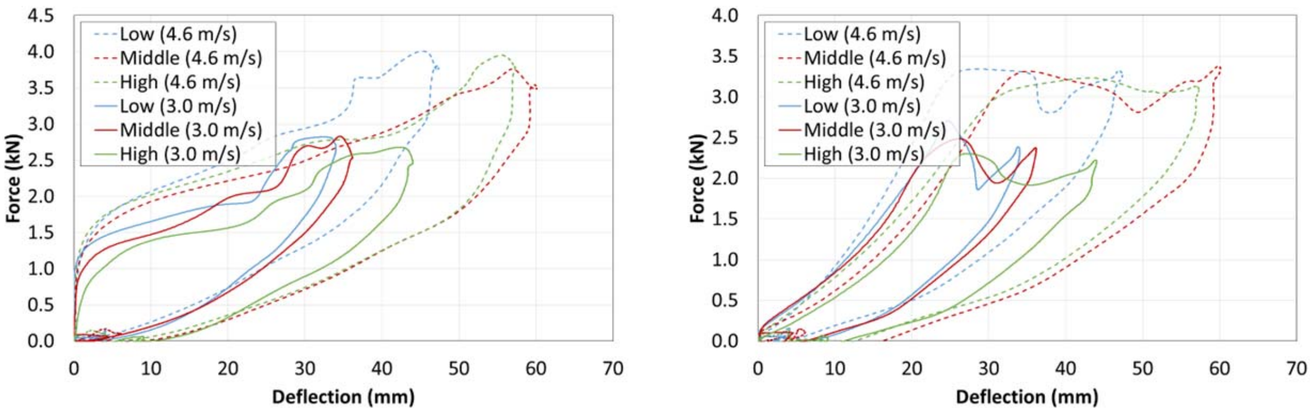


Fig. 8. Effect of shield position: belt (left) and reaction (right) force vs. deflection.

Fig. 9 shows the abdomen pressure vs. deflection response when shield loads were applied in different positions of the abdomen. The greatest pressure for any given deflection was observed in the lowest loading position. This seemed counterintuitive as there was greater engagement with the pelvis in this position and the lowest peak deflection. This can be explained by the kinematics of the shield during these tests and its interaction with the dummy. In this lowest position, the shield largely remained low on the pelvis, but rotated somewhat into the abdomen, particularly in the higher velocity test at 4.6 m/s. In the middle position, some pelvic engagement occurred and the response was similar to that of the low position at the lower velocity. At the higher velocity, however, the shield 'rolled up' the dummy's torso into its chest, reducing abdomen loading but increasing chest loading. In the highest position, limited pelvic engagement occurred and the shield rolled and, in the high velocity test, slid up the chest, loading the rib cage much more so than the abdomen. Such rolling and sliding of the shield would be impossible when it is part of a CRS, because its position would be maintained by guides.

Fig. 10 shows the pressure vs. force response with the shield. The relationships were reasonably consistent across all loading positions and test velocities. Nevertheless, a slightly higher pressure was observed for any given force when the shield was in the low position, for the reasons explained above.

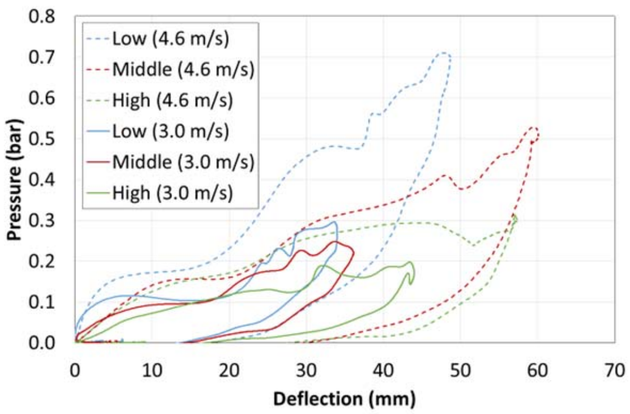


Fig. 9. Effect of shield position: abdomen pressure vs. deflection.

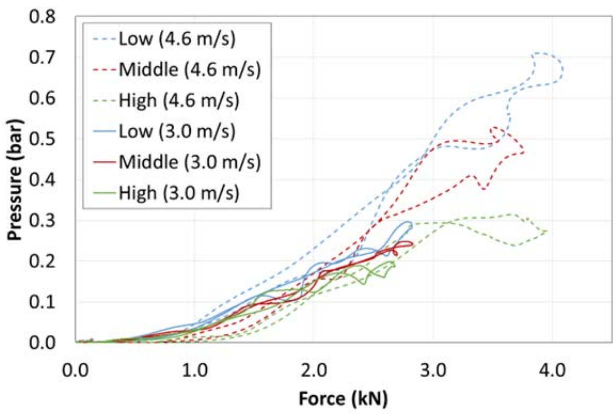
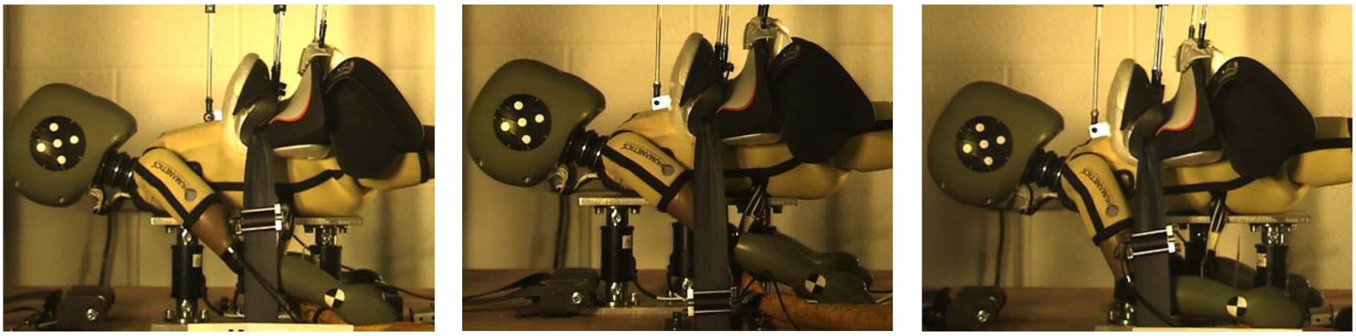


Fig. 10. Effect of shield position: abdomen pressure vs. belt force.



Low Middle High

Fig. 11. Shield interaction with the Q3 abdomen in each loading position (3.0 m/s tests).

Effect of restraint surface on abdomen response

Tests with the middle loading position and lower loading velocity (3.0 m/s) are used below to highlight trends in the effect of the loading surface (belt only or with shield) on the abdomen response. These conditions were chosen and to minimise the influence of the pelvis and rib cage in deriving the abdominal response and because the shield was most stable in these tests. Fig. 12 compares the belt force-deflection response between belt and shield loading. The stiffest response was generated with the shield.

Fig. 13 shows the abdomen pressure vs. deflection response. The belt-only test generated the greater pressure for any given deflection. The peak pressure was very low with the shield, compared with the belt loading test, despite there not being such large differences in the peak deflection. Fig. 14 shows the pressure vs. belt force. The belt generated a higher pressure than the shield for any given force. The results provide some evidence that a shield can reduce pressure (and deflection) generated in the abdomen of the Q3 dummy. That said, it is difficult to make a direct comparison of its effects on the abdomen in isolation as the greater size of the shield meant that it probably engaged with other parts of the dummy during the test.

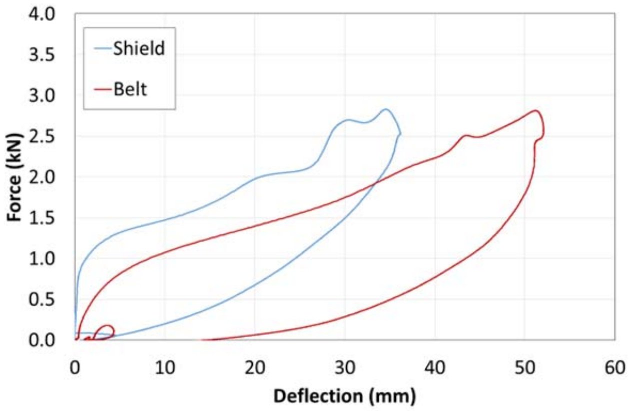


Fig. 12. Effect of restraint surface: belt force vs. deflection (middle position, 3.0 m/s).

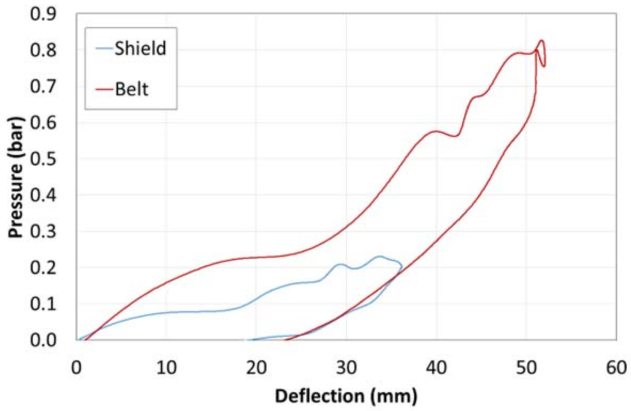


Fig. 13. Effect of restraint surface: abdomen pressure vs. deflection (middle position, 3.0 m/s).

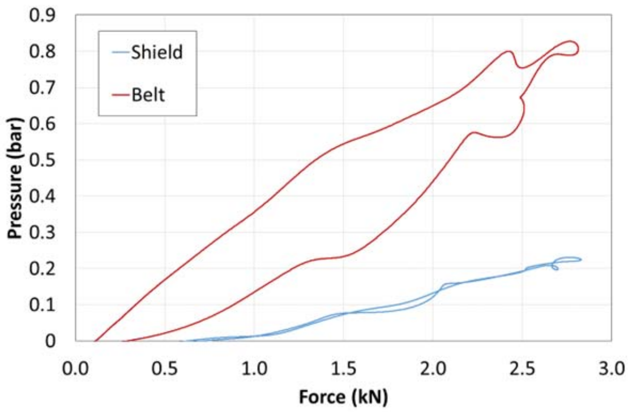


Fig. 14. Effect of restraint surface: abdomen pressure vs. belt force (middle position, 3.0 m/s).

IV. Discussion

The APTS increased the stiffness of the Q3 abdomen in these table-top tests with dynamic restraint loading. This finding differed from that of Beillas *et al*., who observed very similar responses between abdomens with and without APTS [12]. That study used a material testing machine to deliver moderate-rate loading to the abdomen. It is possible that the higher rate loading used in this study enabled the differences to emerge. However, whilst this appeared to be a real trend, further testing would be needed to verify that the differences were greater than typical variation expected between different Q3 dummy abdomens.

The Q3 abdomen and the APTS were sensitive to the location of belt loads applied to the abdomen. The force, pressure and deflection responses generally reflected the interaction between the belt and the dummy parts it came into contact with (i.e. pelvis, abdomen and rib cage). The stiffest response was observed in the lowest loading position, where the belt engaged with the pelvis of the dummy. This sensitivity did not extend to the pressure response, however, since negligible pressure was generated in this position. Beillas *et al*. concluded this was acceptable behaviour for the sensors on the basis that belt forces applied below the anterior superior iliac spines (ASIS) are not thought to be a common source of abdominal injuries [12]. It can be explained further, however, by the characteristics of the APTS. The twin bladders descend ('cap down') into the lower abdomen to a distance of around 20 mm below the ASIS of the Q3. As the pressure sensor is mounted in the aluminium cap, the APTS are incapable of measuring pressure differences in this lower abdomen region at or below the ASIS. This approach to the sensor design, and the underlying assumption behind it, may be valid; nevertheless, appreciable levels of deflection were observed when the belt was in this position. From a restraint design perspective, the APTS may not provide much incentive for a child restraint manufacturer to control the belt path and loading below the ASIS.

The abdomen and APTS displayed reasonable sensitivity to the location of shield loading, although this was influenced by the stability of the shield in some test conditions. Every effort was made to ensure that the shield maintained its stability throughout the test, but it was designed to fit into guides and be part of a CRS. It was impossible to replicate the positioning and securing of the shield in these tests. That said, trends were observed that were consistent with the interaction between the shield and dummy, even in the case where the shield rotated or tilted, since this was also reflected in the dummy response. When the shield was in the lowest loading position, it engaged with the pelvis from the outset of the loading. This generated lower peak deflection than the other loading positions, but the pressure tended to be higher. Although this appeared counterintuitive, it was explained by movement of the shield in the middle and higher loading positions, away from the APTS and into the rib cage. Such motion of the shield (rotating and sliding) is unlikely to be observed in a real CRS. Shield motion was not reported by Beillas and Soni [13], possibly due to the more controlled nature of the material testing machine used in that study. As a result, Beillas and Soni found that both pressure and deflections were lower when the shield engaged with the pelvis.

These dynamic restraint loading tests provided an insight into the APTS and their sensitivities when used with the Q3 dummy. A range of belt and shield loading conditions generated realistic levels of abdominal loading to the Q3. However, the test configuration provided a simplified representation of the loading environment expected in an impact test or real-world collision. During the tests, the dummy was stationary and supine, with motion of the belt generating the impact force and deforming the abdomen. In a frontal impact, the belt would decelerate a moving dummy. Inertial forces may have an important role, therefore, in defining the abdominal response. Furthermore, the dummy would flex and wrap around the belt, or shield, which may also slide up or down the abdominal surface. These kinematic and restraint interaction behaviours were not represented in these tests. Nevertheless, subject to these limitations, these tests generated loads (i.e. abdomen pressure) consistent with those observed in sled tests, in a more controlled way, and enabling the measurement of deflection. They revealed some fundamental characteristics of the Q3 abdomen and APTS response when loaded by a belt or shield. Finally, these findings apply to APTS installed in the Q3 only. Further testing is needed to validate the findings for other dummies in the Q-Series family.

V. CONCLUSIONS

The APTS increased the stiffness of the Q3 abdomen in these table-top tests with dynamic restraint loading. Further testing is needed to establish whether the differences were within reasonable variation expected between different Q3 dummy abdomens. The Q3 abdomen and the APTS were sensitive to the type and location of the restraint loads. Engaging the pelvis of the dummy is likely to reduce deflection and pressure for a given force for any restraint type. However, the APTS do not descend fully into the pelvis and hence it may be possible to load the abdomen in front of the pelvis in a region not covered by the sensors. The risk of abdomen injury may be less when the restraint engages with the pelvis; nevertheless, relatively high deflection was observed with negligible pressure in our belt loading tests in the lowest loading position.

VI. ACKNOWLEDGEMENT

The table-top tests were carried out by TRL. The authors acknowledge the support of TRL's test team in completing the tests.

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