Abdominal Biofidelity Assessment of 50th Percentile Male and 10-Year-Old ATD Responses Relative to a Recently Developed Belt-Loading Corridor

R. Ramachandra, Y-S. Kang, A. Hagedorn, J. Stammen, J. Bolte IV

Abstract This study investigated the biofidelity of anthropomorphic test device (ATD) abdomens subjected to a belt loading test condition. A total of six ATD/abdomen insert combinations were subjected to belt loading using a seatbelt pull mechanism, with the ATDs seated upright in a free-back configuration. Three 50th percentile male ATDs were tested, including THOR-K, Hybrid III 50th percentile male with reusable rate-sensitive abdomen (HIII-50M RRSA), and Hybrid III 50th percentile male with standard abdominal insert (HIII-50M). Additionally, three 10-year-old (10yo) size child ATDs including Large Omni-directional Child (LODC), Q10, and HIII 10yo were tested and evaluated. Force-penetration results of the 50th percentile male ATDs were compared directly to a belt loading corridor derived from post-mortem human subject (PMHS) testing in this test configuration, while 10yo ATD responses were compared to a scaled version of the corridor. Biofidelity of the ATD abdomen responses under free-back seatbelt loading condition were quantified using the NHTSA Biofidelity Ranking System *(BioRank)*. Among the adult ATDs, HIII-50M, HIII-50M RRSA and THOR-K scored 1.99, 1.71 and 1.33 respectively, indicating that the THOR-K has a response closest to PMHS. All three child ATDs displayed responses that were outside of the scaled PMHS corridor. The child ATDs showed surprisingly similar responses even though their abdominal area structures are quite different.

Keywords abdomen, biofidelity, LODC, seatbelt, THOR.

I. INTRODUCTION

Abdominal injuries caused by blunt or penetrating trauma such as those experienced in motor vehicle crashes (MVCs) may be life threatening, especially due to the lack of early symptoms which may lead to a diagnosis that is too late. For instance, in an event of blunt trauma to the abdomen, a vascular insufficiency leading to bowel necrosis may not manifest until hours after the event. Due to the considerable risk of abdominal injuries to both adults and children in MVCs as shown by various studies [1-4], it is desirable to have an anthropomorphic test device (ATD) abdomen that would evaluate injury risk in all types of car crashes.

Measuring the risk of abdominal injuries with ATDs is a challenge from both a biofidelity and instrumentation standpoint. It is difficult to accurately represent the viscoelastic, heterogeneous nature of the human abdomen and organ mobility in response to loading. It is also a challenge to develop viable instrumentation to measure belt penetration in such a soft component. The lack of a biofidelic response may lead to inaccurate conclusions while evaluating motor vehicle safety systems. To evaluate and improve upon the biofidelity of an ATD abdomen, data from ATD tests should be compared to published response corridors based on laboratory tests using post-mortem human surrogates (PMHSs) under identical test conditions. Additionally, an ATD should be capable of measuring parameters that are relevant to prediction of injury when subjected to crash loads. Several studies have investigated various metrics for both injury and response prediction that have led to the development of newer abdomen inserts [5-8].

The abdominal insert for the Hybrid III 50th percentile male (HIII-50M) is made of urethane foam covered with vinyl skin and fills the space in the pelvis. It is somewhat elliptical in shape and has no instrumentation to measure abdominal injury in addition to not having a biofidelic mechanical response [9]. In order to demonstrate rate-sensitivity and good biofidelity under various loading conditions, [10] developed a Reusable Rate-Sensitive Abdomen (RRSA) for use within the HIII-50M. The RRSA insert comprises of a bladder made of

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silicone rubber filled with silicone gel silicone gel within a thick silicone shell and this insert performed well compared to the PMHS abdomen response data of [11] under rigid-bar, seatbelt, and airbag loading. The THOR-K abdominal insert consists in a single foam block within a vinyl skin layer equipped with bi-lateral three-dimensional IR-TRACC (InfraRed Telescoping Rod for Assessment of Chest Compression) devices measuring deflection and angle variation [12].

Studies suggest that child occupants in the 6-12 year old age group are especially susceptible to lap belt-induced abdominal injuries if their stature is not appropriate for seatbelts [2][5]. These studies also indicate that having a way to measure risk of abdominal injury would prevent child occupants from submarining under the lap belt. While the Hybrid III 10-year-old (HIII 10yo) does not directly measure abdominal loading, there have been development efforts to address this necessity. The HIII 10yo abdominal insert is constructed similar to the HIII-50M insert. As a part of the Enabling Protection for Older Children (EPOCh) project, Abdominal Pressure Twin Sensors (APTSs) were introduced into the Q-series ATDs to measure restraint loading to the abdomen [13-14]. The Large OmniDirectional Child (LODC) developed by NHTSA/OSU/TRC is similar in size to the HIII 10yo and Q10 ATDs and also uses the APTS [15].

The purpose of the current study was to compare the responses of different ATD abdominal inserts that are at various stages of development or implementation, to the responses from PMHS tests under identical test conditions [16]. Adult size ATDs evaluated included the Hybrid III 50th percentile male (HIII-50M) with standard abdomen, HIII-50M retrofitted with RRSA, and THOR-K. The child ATDs evaluated were HIII 10yo, Q10, and LODC.

II. METHODS

The seatbelt loading device described in [16] was used to test the ATDs. The device used a pneumatic piston to pull a seatbelt into the abdomen of the ATDs in a controlled, dynamic scenario. The instrumentation used for the ATD tests were identical to the PMHS tests, except for the 3aω motion blocks consisting of three linear accelerometers (Endevco, CA, Model #7264c) and three angular rate sensors (DTS, CA, Model #ARS 8k/ ARS-PRO 18k) on the spine and pressure transducers located within the abdominal vasculature. A string potentiometer (FirstMark, NC, Model #162-3405) was attached to the lumbar spine of the ATDs using a wire-tie to measure displacement of the ATD with respect to the table. To account for any difference in pelvis structure between the HIII 10yo, Q10 and LODC, the belt was positioned at the same height from the table for all three ATDs. Like the PMHS tests, another string potentiometer (Celesco, CA, Model #PT101) attached to the seatbelt webbing in front of the specimen at the level of the umbilicus measured displacement of the belt with respect to the table. Lastly, a linear displacement potentiometer (Penny Giles, UK, Model #SLS190) mounted between the moving ram and its stationary frame measured ram displacement. Abdomen penetration was calculated, as shown in Equation 1, by subtracting the displacement of the lumbar spine at the level of the belt from the displacement of the seatbelt into the abdomen.

$$\delta_{Abd} = \delta_{Belt} - (\delta_{Ram} - \delta_{Lumbar}) \quad (1)$$

where, δ_{Abd} = abdomen penetration; δ_{Lumbar}= displacement of the lumbar spine relative to ram; δ_{Belt} = displacement of seatbelt relative to table fixture; and δ_{Ram} = displacement of ram. Abdomen penetration speed was found by differentiating abdomen penetration. Seatbelt load cells (Denton, Model #5755) were affixed to the belt on the left and right sides of the ATD to measure belt forces. Belt force was calculated as the sum of forces obtained from the two seatbelt load cells.

Fig. 1 shows the pre-test position of the HIII-50M along with the external instrumentation used. Prior to impact, the arms were lifted to shoulder level to ensure that they would not interfere with the movement of the ATD. The legs splayed slightly outward in a natural seated position. The seatbelt was positioned to wrap around the anterior and lateral aspects of the ATD abdomen at the mid-abdomen level. The initial belt tension was adjusted so that each belt load cell measured 15-20 N, to ensure repeatable initial position of the belt with respect to each ATD and remove any slack. Additionally, this initial belt tension was similar to the pre-stiffening load applied to the abdomen in the PMHS study.

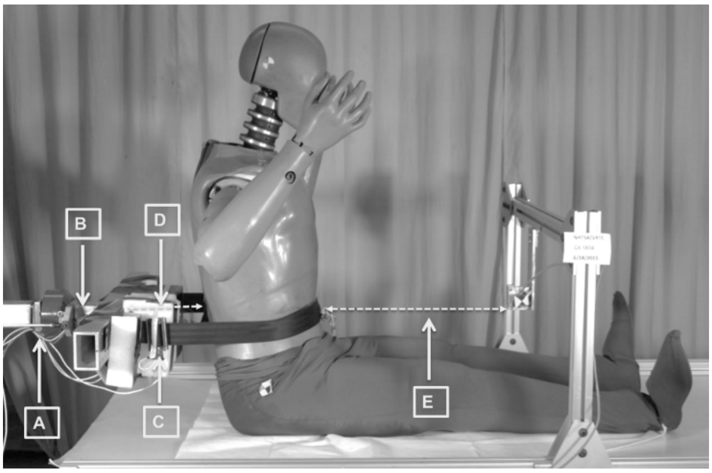

Fig. 1. Pre-test positioning of HIII-50M RRSA on the seatbelt test device (A: Linear potentiometer on ram; B: Force transducer on ram; C: Seatbelt load cell; D: String potentiometer attached to lumbar spine; and E: String potentiometer attached to seatbelt).

For all the ATD tests, the chest jacket was used for accurate ATD representation and to take into account the influence of outer flesh/skin on the abdominal response. In terms of input, all six ATDs were tested using an accumulator pressure of 620 kPa, which is the same pressure as Test Condition A for the PMHS tests in [16]. Fig. 2 shows the pre-test positions of the HIII-50M, THOR-K, HIII 10yo, Q10, and LODC on the test apparatus.

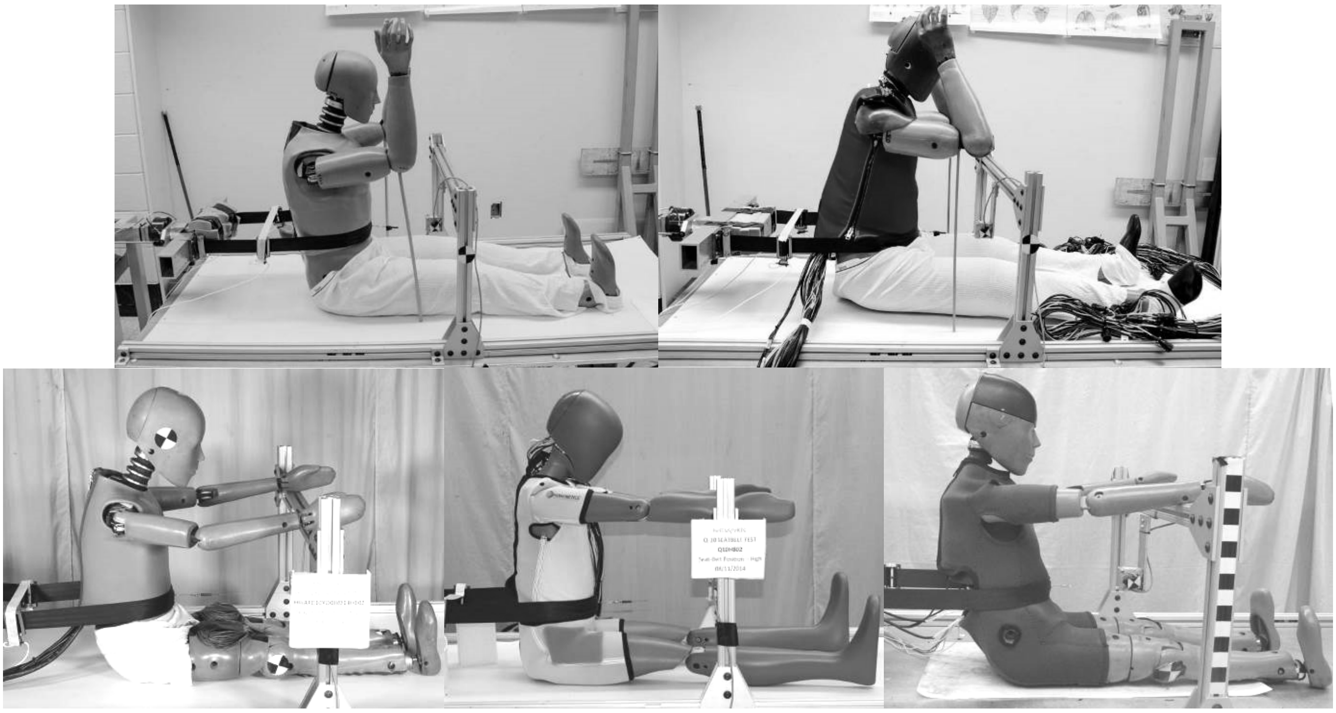

Fig. 2. Pre-test positions of HIII-50M (top left), THOR-K (top right), HIII 10yo (bottom left), Q10 (bottom center), and LODC (bottom right).

Data were acquired at a sampling frequency of 20,000 Hz and in the laboratory coordinate system (LCS), with the positive x-axis directed from posterior to anterior, positive y-axis directed from left to right, and positive z-axis directed from superior to inferior, per standard SAE-J211. Time channels were zeroed when the ram acceleration reached 0.5 g. The force-penetration responses from all the adult ATD tests were compared to the PMHS corridor shown in Fig. 33.

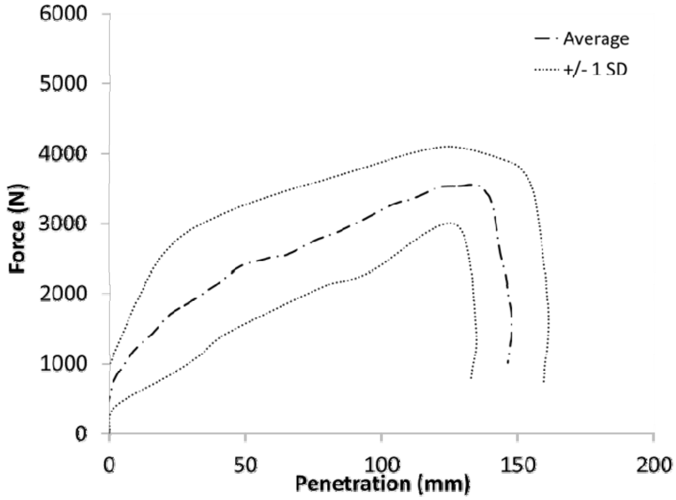

Fig. 3: Force-penetration corridors developed in the PMHS study [2].

In order to quantitatively assess the similarity of the adult ATD responses to the PMHS-based corridor, an objective biofidelity ranking score was calculated using the methodology described by [17]. The force and penetration channels were first brought to a common time basis across the PMHS and ATD tests. The time zero was established as the first 0.5 g acceleration of the pneumatic ram. The calculation included the middle 80 % of the event considering the peak force and peak penetration for each test. Equation 2 shows the calculation used for generating a biofidelity score. The √R value corresponds to the ratio of cumulative variance between the ATD response and mean PMHS response over the cumulative variance between the mean PMHS response and mean plus one standard deviation. A lower value of the Biofidelity Rank (BR) represents better biofidelity.

$$BR = \frac{\sum_{i=1}^{l}\left[\frac{\sum_{j=1}^{m}\left[\frac{\sum_{k=1}^{n}\sqrt{R_{i,j,k}}}{n}\right]}{m}\right]}{l} \quad (2)$$

where R = response measurement comparison value, , i = body region, j = test condition, k = response measurement , l = number of body regions = 1 (abdomen), m = number of test conditions = 1 (seatbelt loading), and n = number of response measurements per test condition = 2 (force and penetration). The BioRank calculations were done using force-time and penetration-time histories, and not using force-penetration.

Scaling Normalised Adult PMHS Data to 10 Year Old

The normalised abdomen force-penetration data obtained from the PMHS study on seven different PMHSs (Fig. 4) were scaled so that the child ATD responses may be compared qualitatively to the estimated abdominal response of a 10yo. Biofidelity ranking scores were not calculated for the child ATDs given uncertainty of how appropriate the chosen scaling method is for this free back abdominal belt loading condition.

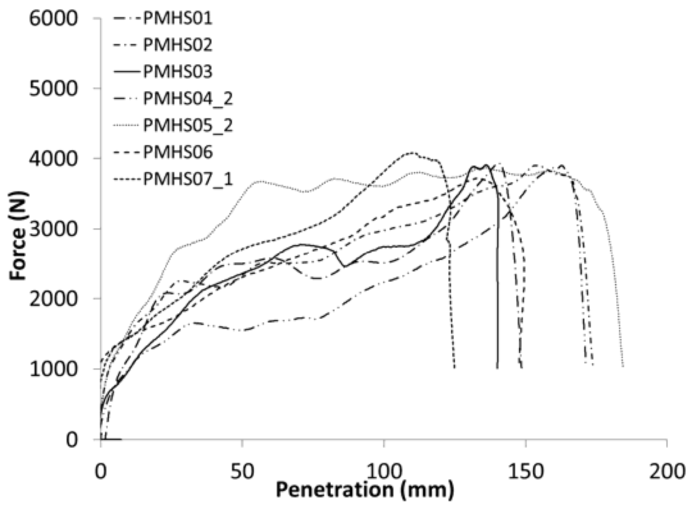

Fig. 4. Adult PMHS abdomen data from [16]

Reference [17] adapted the scaling approach introduced by [18] to derive response characteristics for a 10yo by scaling elastic modulus by age. This was used for scaling the abdominal response in this study (Table I). In Table I, λ_m is the ratio of 10yo mass to the adult PMHS mass, λ_v is the input velocity scale factor (PMHS and 10yo ATDs were tested at the same input ram pressure), λ_L is the ratio of 10yo to PMHS seated abdominal depth, λ_E is the elastic modulus scale factor reported for a 10yo [19], λ_K is the stiffness scale factor calculated as a product of elastic modulus and seated depth ratios, and λ_t is the time scale factor. The approximate response of a 10yo was calculated by multiplying the adult PMHS force, penetration and time data shown in Fig. 4 by R_f, R_p, and λ_t respectively. The average response was calculated from the scaled force, penetration and time data from the seven PMHSs to compare with the HIII 10yo, Q10, and LODC responses.

TABLE I
SCALING FACTORS USING EPPINGER/MERTZ METHOD

Parameters	10yo	PMHS1	PMHS2	PMHS3	PMHS4	PMHS5	PMHS6	PMHS7
M	33.4	56	64	70	86	50	74	67
$\lambda_m = M_1 / M_{ref}$		0.60	0.52	0.48	0.39	0.67	0.45	0.50
$\lambda_v = V_1 / V_{ref}$		1	1	1	1	1	1	1
L	186	358	311	300	300	200	265	265
$\lambda_L = L_1 / L_{ref}$		0.52	0.60	0.62	0.62	0.93	0.70	0.70
λ_e	1	0.854	0.854	0.854	0.854	0.854	0.854	0.854
$\lambda_K = \lambda_E * \lambda_L$		0.44	0.51	0.53	0.53	0.79	0.60	0.60
$\lambda_t = \lambda_E^{-1/2} * \lambda_m^{1/3}$		0.91	0.87	0.85	0.79	0.95	0.83	0.86
$R_f = \lambda_v * (\lambda_m * \lambda_K)^{1/2}$		0.51	0.52	0.50	0.45	0.73	0.52	0.55
$R_p = \lambda_v * (\lambda_m / \lambda_K)^{1/2}$		1.16	1.01	0.95	0.86	0.92	0.87	0.91

III. RESULTS

A total of six ATDs were tested including the HIII-50M, HIII-50M retrofitted with RRSA, THOR-K, HIII 10yo, Q10 and LODC. All tests were conducted at the baseline accumulator pressure of 620 kPa to be consistent with the input used to develop the PMHS corridor.

Fig. 5 shows the responses of the three 50th percentile ATDs tested in comparison with the PMHS corridor. Table II catalogues the peak force, penetration and compression results for the adult ATDs.

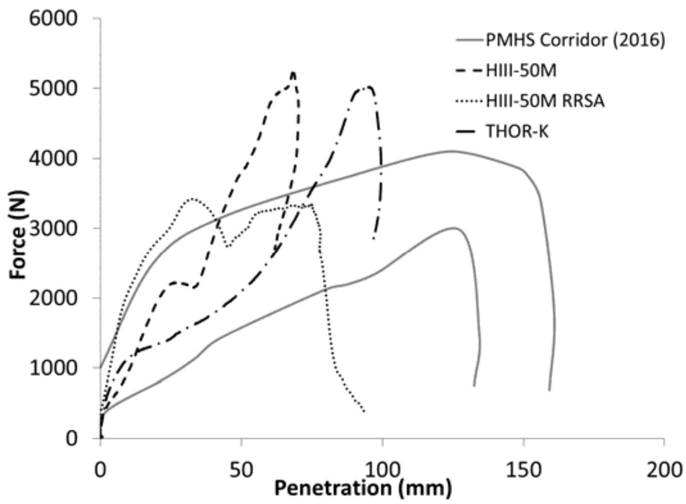

Fig. 5. Comparison of the force-penetration responses of HIII-50M, HIII-50M RRSA and THOR-K to the PMHS corridor.

TABLE II
SUMMARY OF VALUES RECORDED AND CALCULATED FROM THE ADULT ATD TESTS

Test ID	Peak Force (kN)	Peak Penetration (mm)	Compression (%)
HIII-50M	5.25	70	28
HIII-50M RRSA	3.42	93	37
THOR-K	5.02	100	40
PMHS [12]	2.90-4.80	110-177	45-59

Fig. A1 in the Appendix shows the adult ATD responses compared to PMHS biofidelity targets. Table III shows that the Biofidelity Rank of THOR-K abdomen is better than the other ATDs tested under similar input conditions. All three abdomens demonstrated overall BR under 2.0, suggesting a biofidelic response [20]. With a difference in Biofidelity Rank of over 0.2 between each other, the three ATD abdomens are considered significantly different from each other with respect to biofidelity [17]. Overall, the THOR-K abdomen had the lowest √R indicating the most biofidelic response in this particular test configuration.

TABLE III
BIOFIDELITY RANKS FOR ATDS

Measurement	HIII-50M	HIII-50M RRSA	THOR-K
Force-Time	1.29	1.07	1.18
Penetration-Time	2.69	2.36	1.48
Overall	1.99	1.71	1.33

Fig. 6 shows the force-penetration responses from the 10yo child ATDs in comparison to the scaled corridor.

Fig. A2 in the Appendix shows the child ATD responses with the Mertz scaled/normalised large child biofidelity targets. Table IV catalogues the peak force, penetration and compression for the child ATDs.

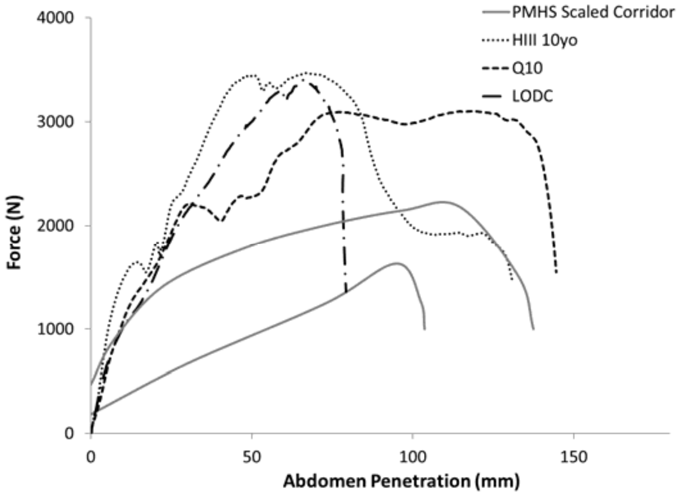

Fig. 6. Comparison of the force-penetration responses of HIII 10yo, Q10 and LODC to the average +/-1 SD scaled response from PMHS tests.

TABLE IV
SUMMARY OF VALUES RECORDED AND CALCULATED FROM THE CHILD ATD TESTS

Test ID	Peak Force (kN)	Peak Penetration (mm)	Compression (%)
HIII 10yo	3.47	131	70
Q10	3.10	144	75
LODC	3.40	82	45
PMHS Scaled	1.60-2.15	105-140	57-76

IV. DISCUSSION

In this study, adult PMHS abdominal response data were compared to adult ATD response data in order to evaluate the biofidelity of the HIII-50M, HIII-50M RRSA, and THOR-K abdomen. Secondly, the adult PMHS data were scaled to estimate a 10 year old abdominal target response and that scaled response was then compared with HIII 10yo, Q10 and LODC.

For the purposes of ATD evaluation, it is important that a biofidelity test condition have a consistent input. The test-setup used in this study achieves this objective as it is a more repeatable, better-defined test condition than previously published corridors [11][21] and therefore more appropriate for ATD development and evaluation purposes. While the abdomen of the subject may influence the overall stroke of the ram, such a response is identical to all other component-level biofidelity tests where a known input velocity is applied but once contact with the specimen or ATD is made, the impactor is affected by what it contacts.

The initial stiffness of the HIII-50M with RRSA was higher when compared to the PMHS tests (see Fig. 5). It is likely that the shifting of organs and contents in the abdominal compartment upon distributed loading is not captured in the RRSA, in turn resulting in a higher initial stiffness response of the abdomen. When seated, the abdominal contents of the PMHS, like in living humans, are brought downwards, especially when the lungs are filled during a deep inhale and the organs are allowed to move freely away from the belt loading path. However, a study conducted by [22] using a fixed-back configuration with the PMHS in inverted position similar to [23] suggested that the initial position of abdominal organs, especially the liver, with respect to the impactor plays an important role in the internal organ kinematics and overall response.

On the other hand, the THOR-K abdomen exhibited an initial response that is similar to the response recorded in PMHS tests. There was an evident soft behaviour until approximately 45 mm, which is similar to the PMHS response in the current study, after which there is an increase in stiffness until reaching a peak force of 5 kN and penetration of 100 mm. Additional tests with the THOR-K abdomen under various loading rates may provide information about viscous and damping characteristics. While it may be argued that the pre-stiffening load of 15-20N applied on the belt may possibly confound the toe region of force-penetration, it is unlikely that the biofidelity was affected since there was little to no initial penetration due to the belt pre-load.

The sudden dip in force of HIII-50M RRSA around 40 mm penetration was caused by the belt sliding off into the gap between the chest jacket and pelvis and continuing to load the abdomen directly. This phenomenon is highlighted in Fig. 7 that shows the post-test position of belt trapped under the pelvis skin and in contact directly with the abdomen. When the HIII-50M housed the standard abdominal insert, there was very little gap between the pelvic rim and the jacket lip as the torso flexes forward slightly with the original lumbar spine assembly. However, the initial gap was more pronounced with the RRSA as it uses a modified lumbar spine assembly that extends the torso slightly and a belt slippage may be expected in an actual full-scale vehicle or sled testing. Although there was a slippage, the belt continued to load the abdomen after it went between the pelvis and chest jacket, which may be considered a response characteristic of the abdomen. Further investigation is necessary to identify the variation in BRS without the slippage. In order for the RRSA abdomen to drive the overall force-penetration response and minimize the risk of this slippage occurring in a sled or vehicle test, it may be necessary to remove the anterior pelvis skin similar to how the abdomen is configured in the LODC and Q10.

Fig. 7. Initial placement of seatbelt on the Hybrid III with RRSA (left); final position of seatbelt trapped between the chest jacket and pelvis (right)

To provide a more direct comparison for the child ATD abdominal responses, the scaling approach suggested by [18] was applied to the adult PMHS data. The scale factors reduced the force by almost half while only slightly reducing the penetration (R_f average =0.54, R_p average = 0.95). All three child ATDs displayed responses that were outside of the scaled PMHS corridor. The child ATDs showed surprisingly similar responses even though their abdominal area structures are quite different. This similarity is likely due to the child ATDs being lighter than both adult PMHS and ATDs, which indicates that the inertial effect (child ATDs are similar in mass to one another) is dominating the response in the free back condition, whereas in the fixed back condition, the abdomen stiffness is dominant. More investigation is needed to develop an appropriate pulse for evaluating the biofidelity of child ATDs in the free back condition, given the apparent lack of response sensitivity to abdominal designs.

In addition, the free back condition is likely influenced more by pre-test ATD positioning than the fixed back case. All three child ATDs having different pelvic structures, along with differences in the abdomen construction. The Q-series ATDs have a more rounded abdomen and exhibit a more flexed posture [24] compared to HIII 10yo and LODC. The Q10 in the current study starts out much more upright when seated compared to the HIII 10yo and LODC due to differences in the construction of the spine. Compared to the HIII 10yo and LODC, the Q10 exhibited a greater penetration and a reduced belt force, which may be due to the higher flexibility of the torso leading to the softer abdominal response in addition to the different starting positions (Fig. 8). The Q10 response had drop in force, like the RRSA, but there was no belt slip. However, in the Q10 tests, the belt was trapped between the ribcage and the pelvis upon forward flexion. Such a response may be similar to what may be seen in a sled test. However, it must be noted that this forward flexion occurred very late in the event, after maximum penetration had been reached. Although there was forward flexion, such as what may be seen in a sled test, the authors are confident that the abdomen response was not influenced by dummy flexion or pelvis movement over the first 80 msec.

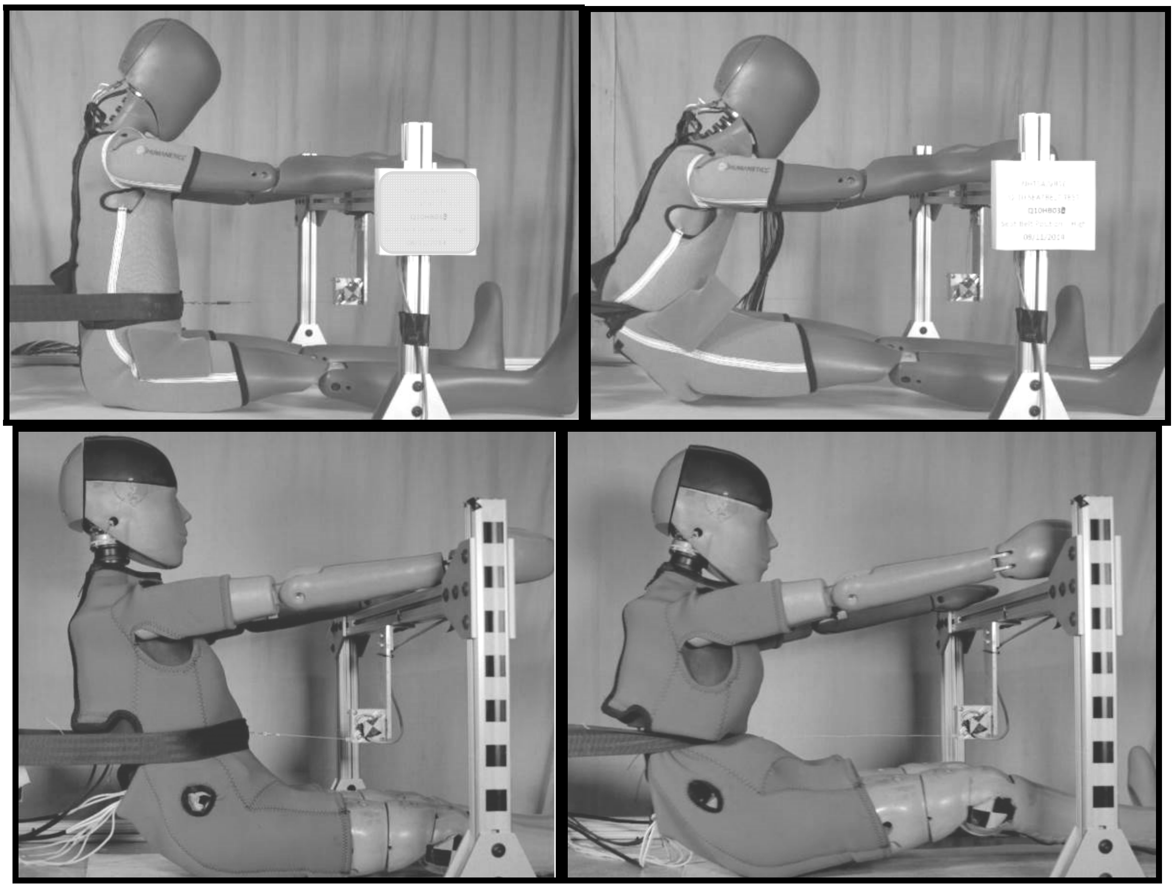

Fig. 8. Q10 (top) and LODC (bottom) in the starting position (left) and at peak penetration (right)

The LODC on the other hand does not exhibit as much flexion which may be attributed to the abdominal stiffness as the belt begins to disengage from the abdomen much sooner than the Q10 and the LODC begins to translate rearward. The HIII 10yo also had a similar abdomen-belt interaction such as the LODC, although the rearward translation occurred sooner indicating a stiffer abdomen characteristic of the HIII 10yo. Differences in pre-test positioning may be compensating for differences in abdomen response among the child ATDs. Further quantitative analysis of the change in torso angle through the event is required to evaluate the differences in abdominal responses of Q10 and LODC.

While the fixed back setup provides an effective characterisation of isolated abdominal response in terms of biofidelity, one of the key benefits of a free-back belt loading setup is that for a given input of the pneumatic ram, the free back setup allows the rest of the ATD to contribute to the abdominal response by not constraining the dummy in any way, thereby providing a more accurate representation of how the dummy would be loaded in a crash event. While a Teflon skid was used to minimise frictional effects in both PMHS and ATD tests, it is unclear how much the pelvis and leg contact with the table throughout the event contributed to differences between PMHS and ATD. With lower friction, the ATD may be allowed to slide back more freely rather than allowing the abdomen to absorb much of the energy. However, this effect is assumed to be negligible based on the investigation using high-speed videos and the slippery nature of the Teflon skid.

References [6][25] developed a lower abdomen biofidelity target using a series of fixed back supine tests on porcine specimens developmentally matched to human paediatric ages. These targets however are not appropriate in the current study due to the dissimilar test setups, although the Kent study offers the most direct paediatric data comparison data for the HIII 10yo, Q10 and LODC. Reference [15] evaluated the HIII 10yo and LODC abdomen dynamic responses employing a fixed-back setup similar to but not identical to [6]. It was determined that the LODC response was more consistent with the biofidelity target than the HIII 10yo based on BioRank scores (0.66 vs. 1.61).

One of the possible reasons for the difference between how the LODC abdomen, which is still undergoing development, scored in the fixed back condition and the response with respect to the scaled corridor in the free back condition may be the dependency of this scaling approach on the published elastic modulus scale factor derived using hard tissue such as the cranial bone rather than soft viscera such as in the abdomen. While this approach provided a reasonable comparison for the upper thoracic response in the [26] study, the technique may not be a best possible representation of the paediatric population while examining soft tissue responses. Additionally, in the absence of a comparison between soft tissue stiffness in adult versus child specimens in the same test configuration in the literature, the approach used in this study assumes that age-related differences in soft and hard tissue properties are similar, which may or may not be the case. A comprehensive study of spinal kinematics with focus on spinal rotations that may lead to differences in abdominal response is also warranted.

It is possible that both the force and deflection behavior of each abdomen could be influenced by the instrumentation (such as pressure sensors or IR-TRACC) selected. While further work could investigate the influence of different types of instrumentation within a given abdomen, it is important that the abdomen contain some sensor for the purposes of measuring direct loading to the abdomen.

A limitation of this study is the use of the same accumulator pressure to drive the belt into the abdomen in both the adult and child ATD tests. It may be argued that the input needs to be scaled down when conducting a similar test between adult and child. However, the relationship between accumulator pressure and penetration velocity is highly dependent on the abdomen characteristics (stiffness and damping). Therefore, if the penetration velocity is considered the input to the ATD, it is difficult to determine the appropriate scale factor for accumulator pressure. Further work is required to better understand the input scaling required for child ATD biofidelity assessment in the free back condition.

Another limitation relates to the uncertainty in scaling the abdominal force and penetration responses in both fixed and free back setups. However, when evaluating the responses of the child ATDs, unlike the availability of a direct comparison to pediatric data [6][25] in a fixed back setup, there is not a direct comparison in the free back setup, making the data from current study heavily rely on scaling techniques.

In summary, this study provides an assessment of abdominal response biofidelity between PMHS and ATDs under identical loading conditions. This evaluation is aimed at guiding design improvements for future versions of these ATDs and their abdominal inserts, as well as models that simulate the physical counterparts.

V. CONCLUSIONS

This study investigated the response of ATD abdomens subjected to seatbelt loading using the same test apparatus as PMHS tests under identical loading. Results from these ATDs were compared to force-penetration corridors developed in [16]. The main outcomes are as follows:

- Using the quantitative biofidelity ranking system, the THOR-K resulted in the lowest BR of the adult ATDs indicating a response closest to the target corridor from PMHS study.
- All three child ATDs displayed responses that were outside of the scaled PMHS corridor. The child ATDs showed surprisingly similar responses even though their abdominal area structures are quite different.
- Scaling of adult PMHS data to a child-appropriate response in the free back condition is challenging given sensitivity of the response to non-abdominal factors such as pre-test positioning, frictional and inertial considerations, and different material property-based scale factors of skeletal and organ structures within the lower torso region.
- While the fixed back setup provides an effective characterisation of isolated abdominal response in terms of biofidelity, the free-back belt loading provides a more accurate assessment of how multiple components including the abdomen contribute to the overall ATD lower torso response.

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VII. APPENDIX

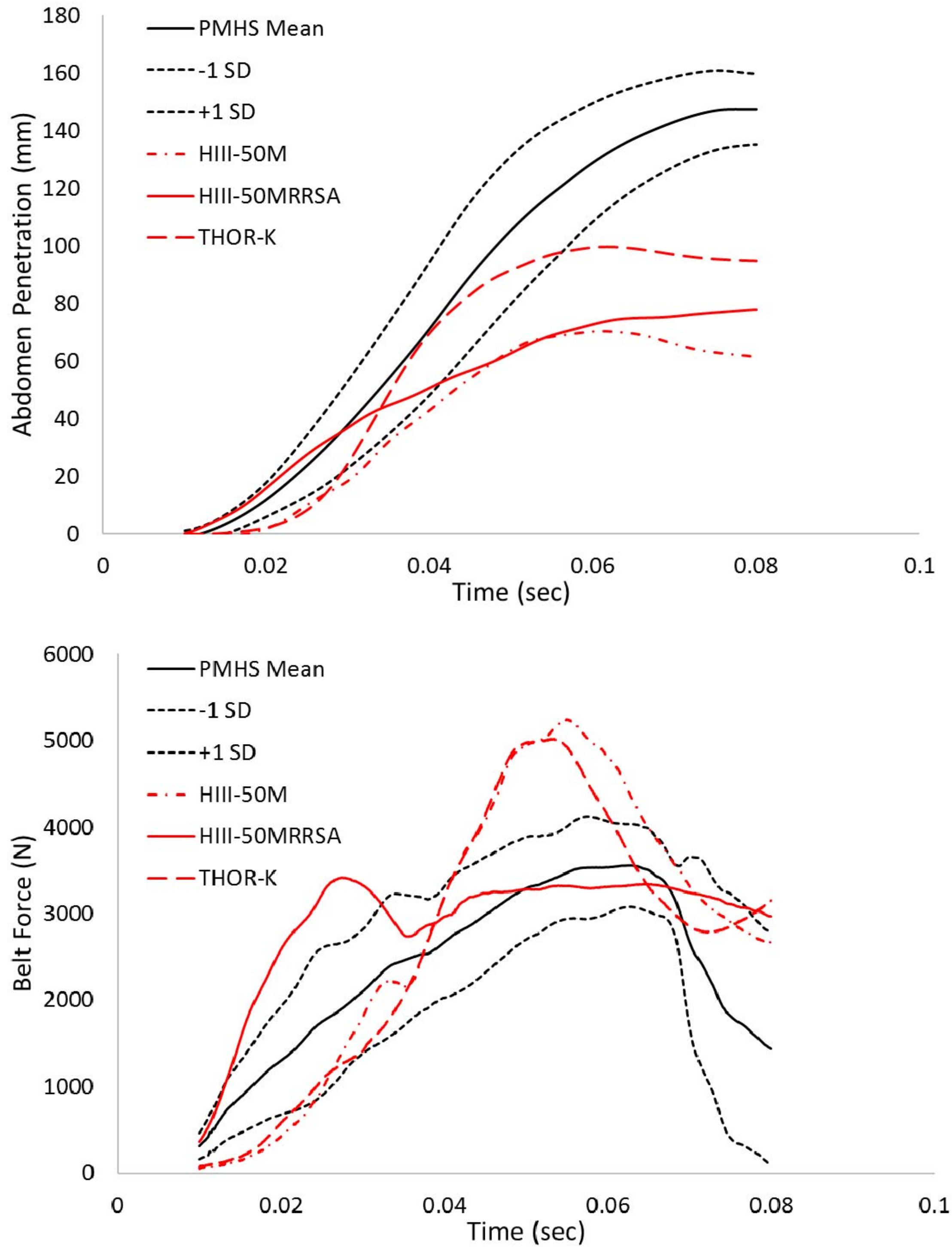

Fig. A1. Adult ATDs abdomen penetration vs. time (top) and belt force vs. time (bottom) responses compared with PMHS biofidelity targets

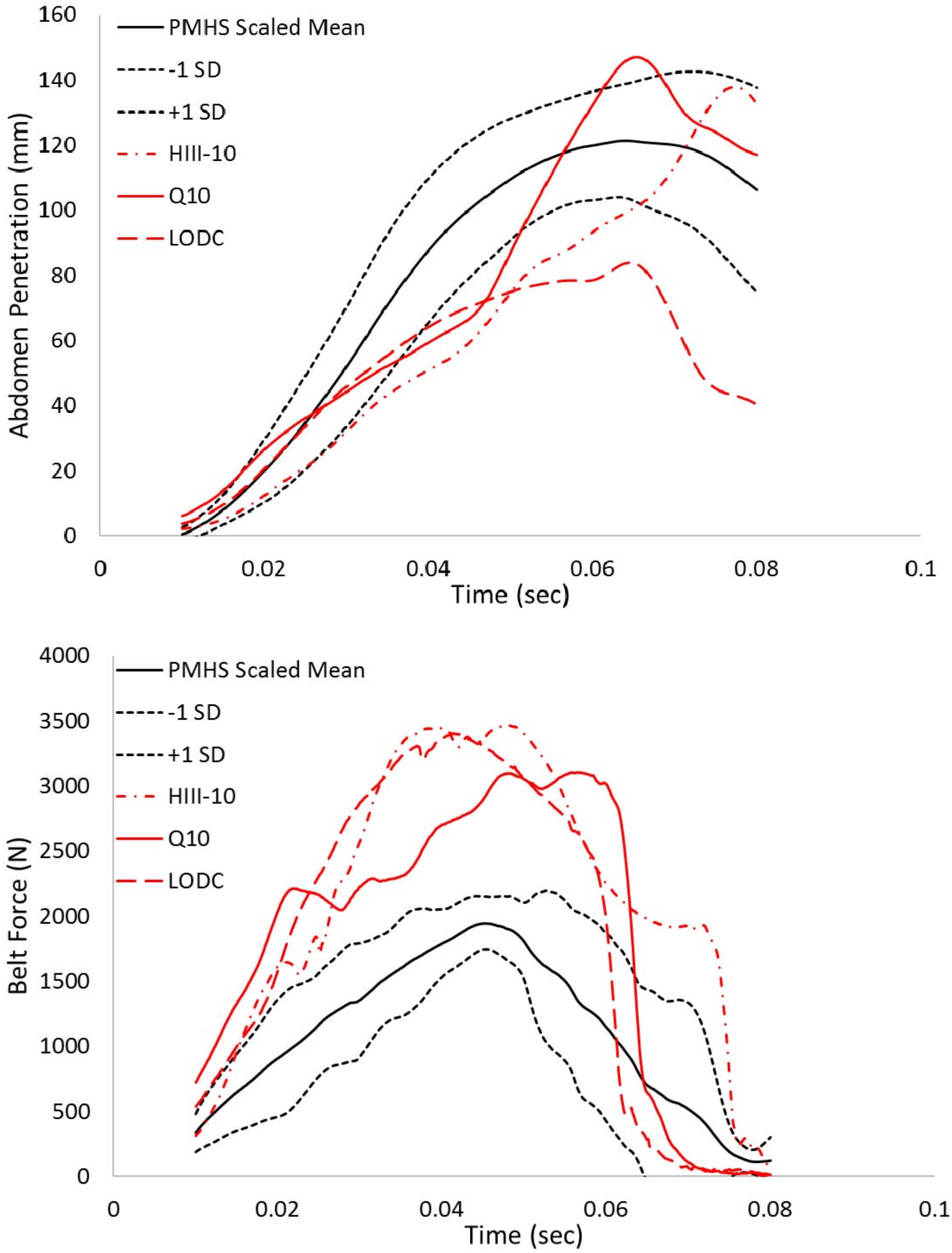

Fig. A2. Child ATDs abdomen penetration vs. time (top) and belt force vs. time (bottom) responses compared with Mertz scaled/normalised PMHS biofidelity targets