The Powered Two-Wheeler Crash Test Dummy Behaviour Compared with PMHS Reference Responses in One Full-Scale Motorcycle-to-Car Collision

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Abstract No complete crash test dummy has been compared with respect to human responses in motorcycle-to-car crash loading. Following previous testing, post-mortem human subject (PMHS) results provided a new target for a human rider in a single full-scale motorcycle-to-car crash scenario. The same crash configuration was recreated with the Powered Two-Wheeler (PTW) Dummy as rider, i.e. a KTM 390 Duke colliding 30 degrees forward of perpendicular into a stationary Honda Accord saloon with the motorcycle travelling at 50 km/h. The dummy test had broadly similar interactions between motorcycle and car, rider and motorcycle and, to some extent, the rider and car. However, differences between PMHS and Dummy (in peak acceleration and duration of loading) occurred in the retention of the pelvis by the fuel tank. In the dummy, subsequent large tensile lumbar spine forces led to an obvious kinematic difference, whereby the head of the dummy hit the roof-rail of the car, whilst the head of each of the three PMHS passed over the top. The PTW Dummy may be a robust tool for use in motorcycle-to-car crash testing, but use of the PTW Dummy in common crash configurations, like this front-of-the-motorcycle into the side-of-the-car case, could underestimate the risk of thoracic injury.

Keywords Biofidelity, motorcycle-to-car collision, PMHS reference responses, Powered Two-Wheeler Dummy, injury risk estimation.

I. INTRODUCTION

The Hybrid III frontal impact dummy has been described as the first human-like crash test dummy [1]. This is justified by the dummy design having a biomechanical basis and being compared with available biomechanics data [2]. Subsequent dummies for use in car occupant protection have undergone a similar process of evaluation, including an assessment of how well they match biomechanical data and biofidelity requirements (for example, the rear, side and frontal impact dummies: BioRID [3-5], WorldSID [6-9] and THOR [10-13]). These assessments provide information on the response of the crash test dummy or anthropometric test device (ATD) at the body region level, though many of the reference data sets come from whole-body biomechanical testing.

The design of a Motorcyclist Anthropometric Test Device (MATD) was proposed after the Hybrid started to be used in safety testing, but before many of the later generations of occupant dummies were developed [14]. After assessing merits of contemporary ATDs, the MATD adopted the pedestrian (standing pelvis) version of the Hybrid III dummy as its basis. Modifications were made, but mostly to address sensitivity to loading and replication of injury mechanisms in the lower extremities (for instance, the inclusion of frangible leg bones to avoid load cells with trailing cables [14]). An interesting addition is the attempt to mirror knee bending stiffness based on three post-mortem human subject (PMHS) specimens. The importance of the load path through the knees and femurs for a motorcycle-riding dummy was used as the rationale for further biofidelity assessments regarding the composite tibia and femur parts [15], comparing with data from the Universities of Tennessee and Louisville. At that time there was discussion around:

“ a) number and causation of leg bone and knee ligament failures
b) head trajectory and velocity
c) head maximum resultant acceleration
d) overall predicted injury severity and injury costs”.

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There was, however, no discussion or evidence to evaluate whether the dummy was a suitable tool to assess those points. Of interest is the comment, made at that time, that the MATD (and therefore the Hybrid III) chest had “inappropriate thorax compliance”. No other mention was made of the MATD’s biofidelity beyond an ability to determine cause-effect relationships for leg fracture phenomena.

The Powered Two-Wheeler Rider Dummy (PTW Dummy) is also based on the standing Hybrid III [16], but with adaptations for use as a PTW riding dummy. The adaptations are not the same as the MATD, with a stated preference towards the use of a small set of bespoke parts and, where necessary, the incorporation of parts previously made and used within other dummies. It doesn’t adopt the frangible bones of the MATD, but rather keeps the original steel bones. Rib-cage components are standard Hybrid III, again excluding the deformable abdomen option. New adaptors are used to link the pelvis to the straight lumbar, to the thoracic spine box, and to the neck. This means that the parts of the PTW Dummy controlling its motion in a crash are likely to have been validated in another dummy already – particularly at the component level (for example, the WorldSID neck) – and that all thoraco-lumbar flexibility is contained within the conventional straight lumbar element. What is already known to be missing is the system-level or whole-body level validation of biofidelity; either between physical and numerical simulation versions, or from the dummy to a human performance reference [17]. Those authors noted that, “Both the chest and the pelvis of the dummy could be reviewed for biofidelity and injury prediction capabilities; though it is not yet clear what are the PTW rider-specific targets for these regions”.

As such, we have potential tools that could be used as a PTW rider surrogate, and Human Body Models (HBMs) will add more options; but we have no means of deciding if they are human-like in their crash behaviour beyond what can be decerned from component-level assessments.

The objective of this study was to take newly derived biomechanical targets for a PMHS in a PTW crash and see how the PTW Dummy performs against them. Where deviations in performance emerge between the dummy and human reference, we are interested to express those in the context of implications for future safety systems. No other evaluation of this type has been undertaken, so there is no need for comparative quantifications yet, rather implications. However, it is intended that the results provided by this study (and the data obtained from the experiment) could form the basis of a tool-to-tool comparison in the future.

II. METHODS

One test condition is available with reference targets for human-like performance in a PTW crash, therefore the method is constrained to a single configuration. The intention was to test the PTW Dummy in that configuration and compare its response with those of the PMHS.

Human Subject Testing

An introduction to the PMHS testing and the likely reference data coming from those tests was given previously [18]. The testing was carried out by the IBRC at The Ohio State University, using a facility at the Transportation Research Center, Inc. (TRC), Ohio, U.S. Each test involved a 50th percentile male PMHS equipped with a Bell Qualifier helmet and seated on a 2022 KTM 390 Duke that was propelled into the side of a 2011 Honda Accord.

PTW Dummy Testing

The testing added by this study was a single test with the PTW Rider Dummy instead of the PMHS. This was run by Autoliv Research in Vårgårda, Sweden. Again, the configuration was matched, so that a KTM 390 Duke collided 30° forward of perpendicular into a stationary Honda Accord saloon with the motorcycle travelling at 50 km/h.

The position of the dummy on the PTW did not follow a specific ‘positioning procedure’. Rather, it was matched, pragmatically, close to the PMHS postures (Table I). Highest priority was given to: the anterior pelvis to fuel tank distance, as this contact created substantial (and injurious) loading into the body of the PMHS, and the thorax angle, as this is a primary factor in the positioning procedure for the MATD in ISO 13232-6. The exact leg positions (angles and orientations) were difficult to manipulate once the pelvis and foot positions were set, rather being a function of leg length and support from the motorcycle. Pre-test images of the dummy or PMHS are shown in Fig. 1. Here it can be noted that the dummy was self-supporting in the pre-test setup. The launcher for the motorcycle included the provision to have guide supports under the armpits, and these were used to reduce vibrations on the approach along the crash track, but they were not essential for maintaining the upright seating position.

TABLE I
PRE-TEST RIDER MEASUREMENTS FOR THE PTW RIDER DUMMY AND THE HUMAN REFERENCE (WHERE ESTABLISHED)

Measurement	**PTW Dummy position**	**PMHS reference**
Side to side alignment	Centre-line (sagittal plane) of dummy on centre-line through saddle	Centred on the saddle
Feet	Feet resting on the foot pins (heel on peg), tip of foot above the brake or gear pedal	
Knees (x-axis) *Knees (z-axis)*	(Forward of rear axle) R: 760 mm, L: 765 mm (Above floor) R: 720 mm, L: 710 mm	
Femur angle	(Downward from horizontal) R: 22° L: 22°	12° to 18°
Pelvis	Crotch to fuel tank distance set to 50 mm	Crotch to fuel tank distance set to 50 mm
Thorax angle	(Forward of vertical) 10.5°	(Forward of vertical) 12°
Shoulder (x-axis) *Shoulder (z-axis)*	(Forward of rear axle) R: 525 mm, L: 520 mm (Above floor) R: 1335 mm, L: 1320 mm	
Upper arm angles	Adduction 17° (target 15°) Flexion R: 25°, L: 33 °	 Flexion: 27° to 30°
Elbow (z-axis)	(Above floor) R: 1085 mm, L: 1100 mm	
Forearm angle	(Down from horizontal) R:12°, L: 13°	(Down from horizontal) 10° to 15°
Helmet (lower edge)	(Down from horizontal) R: 33°, L: 33°	(Down from horizontal) 23° to 27°

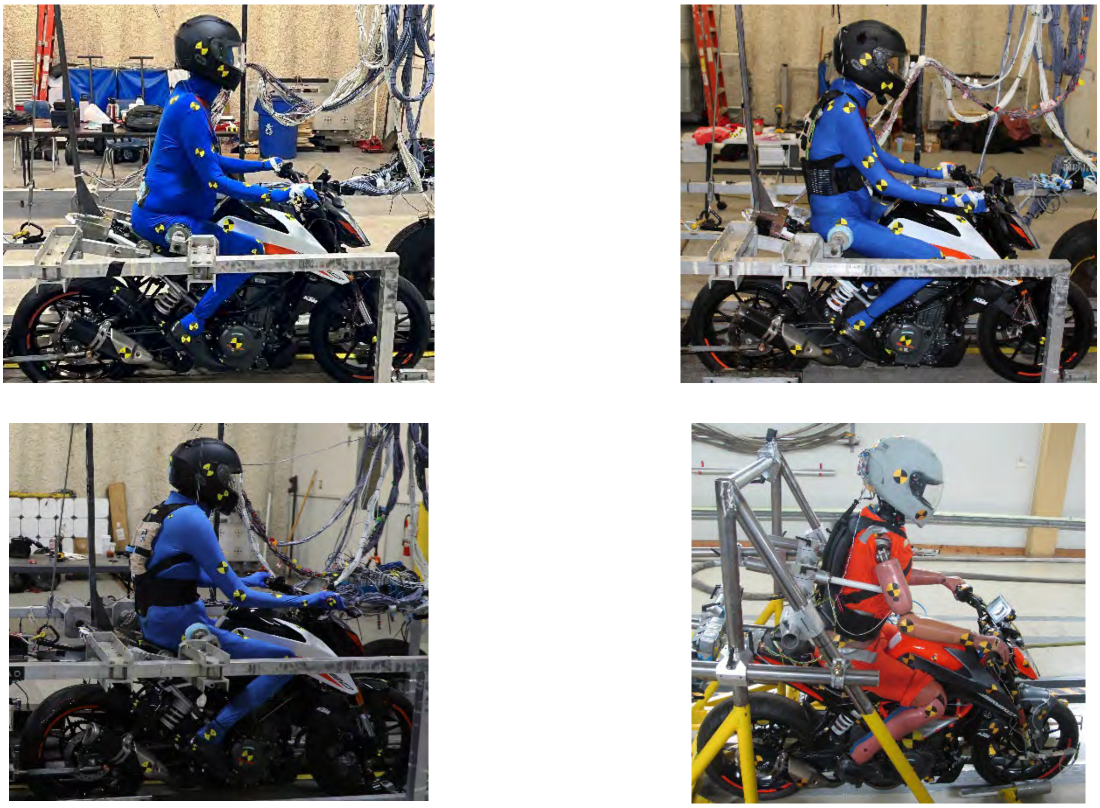

Fig. 1. Images of the rider on motorcycle position pre-test from the three PMHS tests (blue shirts) and the PTW Dummy test (orange shirt).

Comparison between subjects

To compare the biofidelity of the dummy with that of the PMHS, kinematics were used to identify implications for potential safety system countermeasures. Video footage was reviewed, and rider contact points were identified. Beyond this, kinetics were considered also, where dummy instrumentation lent itself to comparison with the PMHS test responses. The dummy instrumentation outputs were reviewed with respect to the nearest relevant measurement available from the PMHS tests (all filtered with CFC180). Corridors were created from the PMHS test data where three equivalent signals were available. The PMHS data peaks were aligned in time and a plus/minus one standard deviation corridor width was used. This means that direct comparisons are limited to the accelerations at the sternum, thoracic spine and pelvis. Head accelerations are also directly compared to two PMHS tests, rather than to a mean response or corridor. These data were acquired via motion blocks at those sites: from six degree-of-freedom inertial measurement units, recording linear accelerations and angular velocities. In the PMHS tests, the units were "DTS 6DXPROunits", from Diversified Technical Systems, Seal Beach, CA, USA. In the dummy, the instrumentation was part of a Kistler (Kistler Group, Winterthur, Switzerland) in-dummy data acquisition installation featuring either 6 degree of freedom units "Kistler DTI5002A06" or tri-axis accelerometers "Kistler DTI-60-3K". A CORrelation and Analysis (CORA) evaluation was used to provide a metric for dummy to PMHS comparisons, using the CORAplus 4.0.4 software and parameter settings as used previously with corridor-based assessments [190].

It should be noted that the exact same model of Honda Accord, eighth generation (as used in the PMHS tests; US Honda Accord, model year 2011), was not available for testing in Europe. The dummy test used a European Accord (nominal height 1440 mm, model year 2011 also), whilst the PMHS tests used an American Accord (nominal height 1476 mm). As well as the nominal vehicle height, other (larger) differences exist between the vehicle models, including the geometry and the door skin and potentially also the underlying lateral impact structures. The KTM 390 Dukes were all model-year 2022 without any known regional or manufacturing differences.

III. RESULTS

Despite using a different version of the Honda Accord (American versus European), vehicle side deformation was similar in the PTW test as with the PMHS tests (example images are given in Fig. 2). The front wing was not deformed in the dummy test as this deformation came from the rider support carriage used in the PMHS tests, not the rider or the motorcycle directly. The profile of the vehicle was scanned (both using a laser system, but of different products) before and after the test, again attesting to similar, though not identical, patterns of deformation (Fig. 3).

Fig. 2. Post-test images of the Honda Accord showing similar deformation patterns from the third PMHS test (American vehicle, left) and the PTW Dummy test (European vehicle, right).

Fig. 3. Images from scanned post-test car side-profiles of the Honda Accord from the second PMHS test (American),

shown above, and the PTW Dummy test (European), shown below.

High-level kinematics

Beyond comparing the post-test deformation of the vehicles, it is also possible to consider the acceleration of the motorcycle as a way of checking the consistency of the PTW Dummy test with the prior PMHS tests. This comparison is shown in Fig. 4, with a CFC60 filter applied to all motorcycle channels. For this and subsequent figures, the blue line represents the mean PMHS test response, the grey shading shows the ±1 standard deviation corridor, and the orange line shows the dummy test response. The initial loading up to 20 ms is almost identical, though later differences are evident, with first a greater drop in acceleration in the PTW Dummy test, then a slightly higher secondary peak (after 40 ms). The reduction in the PTW Dummy test after 60 ms may correspond to more substantial failures in the motorcycle structure, in particular the complete breakage of the triple clamp holding the front fork.

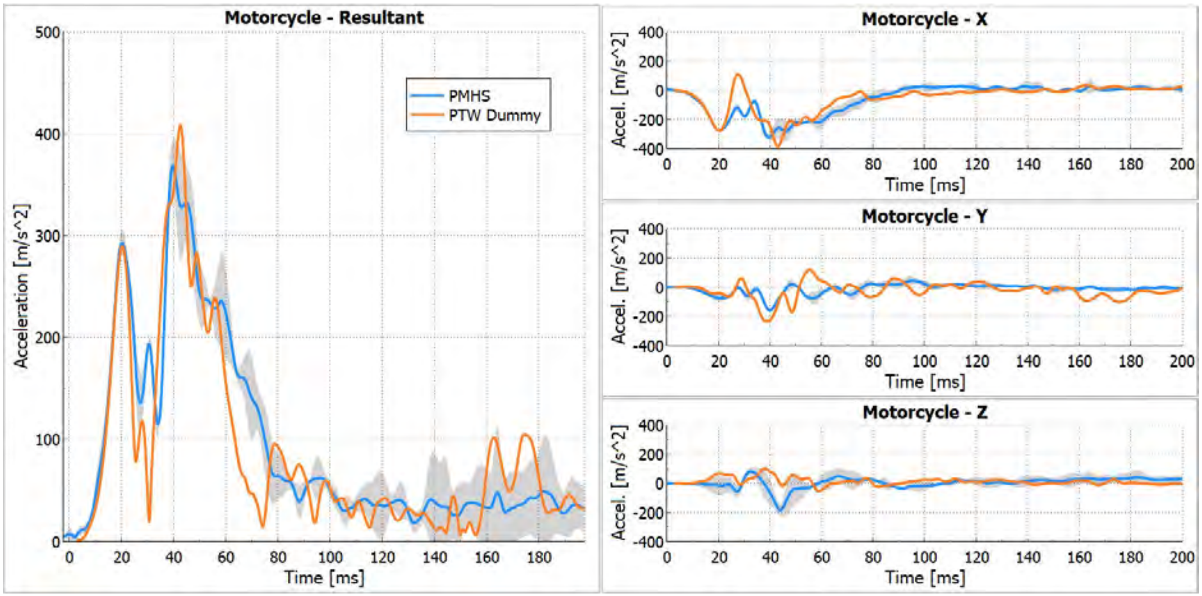

Fig. 4. Pelvis resultant linear acceleration comparison of PTW Dummy response and PMHS (x-, y- and z-axis components on the right).

The principal results, on which conclusions can be drawn with respect to prospective protection systems, are the overall kinematics of the riders. To show the overall trends, images have been extracted from the video-feed of one of the high-speed cameras throughout the series of interest for the second PMHS test and the PTW Rider Dummy test (Fig. 5., note that the 15 ms image is omitted deliberately for pagination).

In these two tests there is very good agreement in the motion of the motorcycle, with similar amounts of yaw and pitch throughout this period of the test. Differences were observed in the amount of pitching within the PMHS tests, so this vehicle-to-vehicle interaction appeared to be within the scale of expected test-to-test variations.

That is not to say that the motorcycle interaction was identical for the dummy test. Indeed, the failure of the upper and lower triple clamp meant that the left tine of the front fork became detached during the test. This failure mode was not seen with the PMHS tests, though the lower triple clamp was noticeably deformed in every test. This indicates that the forces placed on the front forks in the dummy test were greater than in the PMHS tests, even if the overall interaction looked similar.

Broadly, the interaction of the rider followed the same sequence: from the initial deceleration of the motorcycle, the rider’s pelvis closes the gap to the fuel tank and is momentarily restrained there, the handlebars twist leftwards, pushing the right hand through the side window of the car and pushing the left hand backwards, the upper body tips forward about the pelvis, and this presents the right arm and upper thorax to the vehicle side structures, lastly the head continues forward until it is pulled down by the neck onto either the roof or the roof-rail of the car.

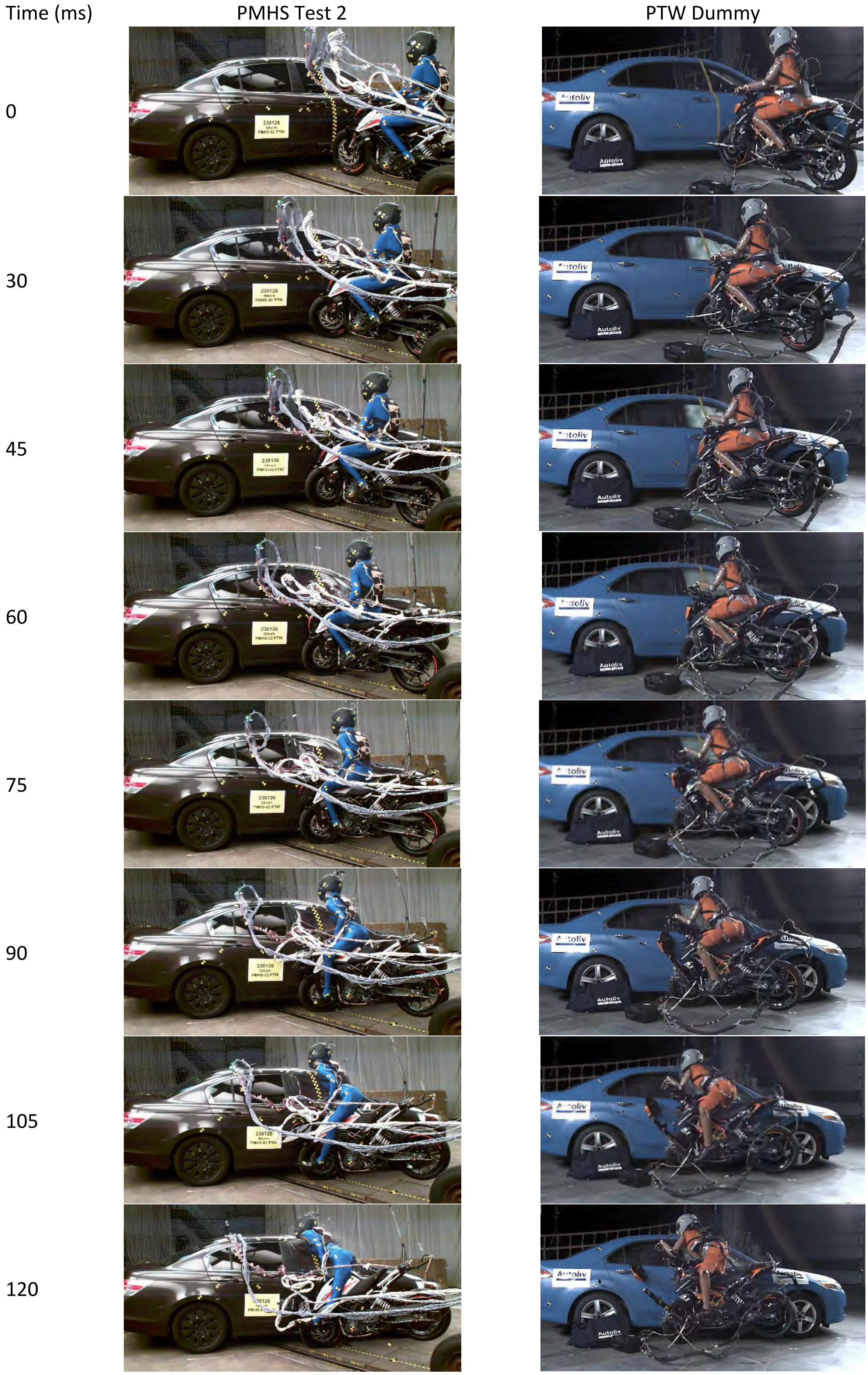

Fig. 5. Still images from the video, showing an overview of the kinematics during the dummy test (right) and the exemplar PMHS test (Test 2, shown on the left).

The trajectories of the body parts point to differences in the details of this sequence. Perhaps due to compliance in the spine, there is modest upward movement of the shoulders and head of the PMHS before the contact with the car, whereas there is no upward movement of the dummy, only downwards. The result of this is that the head of the PMHS rider goes over the roof-rail and hits the roof, whereas the dummy head contacted the roof-rail on the chin bar of the helmet (see images at 105 ms, Fig. 5). From pre-test images we determined that the head of the PMHS in Test 2 was approximately 590 mm above the fuel tank and the head of the dummy was 680 mm above the fuel tank. This is because the PTW Dummy has a more erect sitting posture through the chest and spine. As such, the head to car impact points are not related to (or explained solely by) the pre-impact head height.

Interactions (points of interest)

The time of pelvis contact (based on peaks in the acceleration responses) was a few milliseconds later in the PTW Dummy test (58 ms) than in the PMHS tests (from 51 ms in Test 3 to 53 ms in Test 2). However, at this stage in the impact event little has happened to alter the initial posture for the rider and therefore the posture of the rider looks similar across all tests, as shown in Fig. 6.

Fig. 6. Still images showing the moment of pelvis contact with the fuel tank (PTW Dummy left, PMHS right).

Although, the deformation has not yet been quantified, the imprint of the rider's pelvis in the fuel tank appears broadly consistent amongst the four motorcycles tested (Fig. 7).

Fig. 7. Images showing the deformation of the fuel tank from the PTW Dummy test (left) and the three PMHS tests (right).

Torso contact with the car happened at approximately the same time with the PTW Dummy, at 109 ms, and the PMHS, from 98 ms (Test 1) to 110 ms (Test 2). Images from these times are shown in Fig. 8. As mentioned, head contact was later in the PMHS tests, as the contact point was further around the car surface. It occurred at 104 ms in the PTW Dummy test, but at (for example) 115 ms in the PMHS Test 2.

Fig. 8. Still images showing the moment of torso contact with the car side (PTW Dummy left, PMHS right).

Corridor comparisons

The pelves of the PMHS were instrumented in many places with strain gauges and motion sensors; however, for comparison with the PTW rider dummy, we compare the sacrum-mounted accelerations with those from the back of the pelvis in the dummy (Fig. 9). The main image in the figure shows the resultant accelerations, whilst the right-hand breakdown shows the x-, y- and z-axis comparisons too. Most of the resultant acceleration comes from the x-axis contributions. The data confirm a later engagement of the PTW Dummy pelvis with the fuel tank, but that a higher peak acceleration (of about 500 m/s^2) is seen by the dummy, whilst the PMHS have a plateau at a lower value (around 300 m/s^2) which lasts for longer. The CORA rating for the resultant channel was 0.85 (it was 0.68, 0.59 and 0.65 for x-, y- and z-axes, respectively).

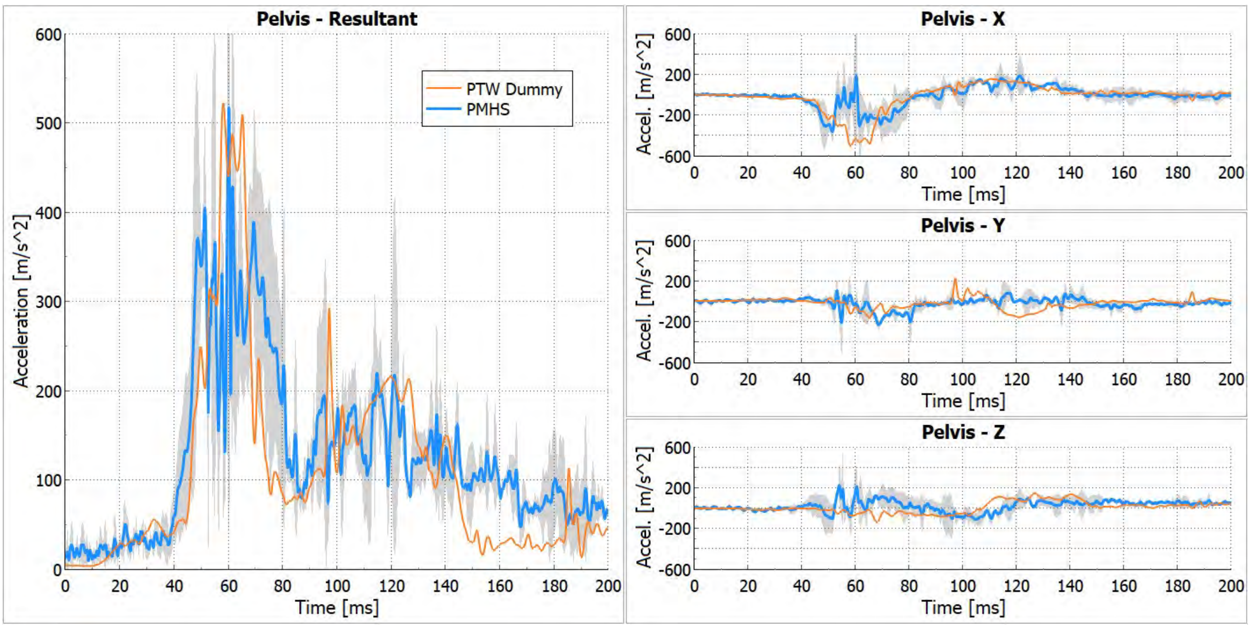

Fig. 9. Pelvis resultant linear acceleration comparison of PTW Dummy response and PMHS (x-, y- and z-axis components on the right).

At the sternum, the PMHS were fitted with 6 degree-of-freedom motion blocks (inertial measurement units – measuring linear accelerations in three axes and angular velocities in three axes). The dummy does not offer the same instrumentation option, but rather two single-axis accelerometers. This facilitates comparison of the x-axis accelerations at least, as shown in Fig. 10. The initial impact between the PMHS and the car was high on the torso, probably above the sternum instrumentation, although it was sufficient to create a sternum fracture in all three PMHS tests. In the PTW Dummy, the upper sternum position measured a greater peak acceleration than the lower position (799 or 476 m/s2) and is a closer match to the magnitude from the PMHS tests; given this and the high contact locations, the upper sternum sensor is used for the data comparison. All tests produced a peak acceleration over 600 m/s2; however, the timing is delayed in the dummy test with respect to the peak loading from the PMHS tests. The CORA rating for the sternum acceleration was 0.65.

The Hybrid III rod potentiometer in the chest of the PTW Dummy measured a peak of 6.1 mm chest deflection at 113 ms, indicating a negligible risk (0.5%) of serious thoracic injury based on that sensor output. In the PMHS, numerous rib fractures were observed yielding AIS3+ thoracic injuries in all three tests.

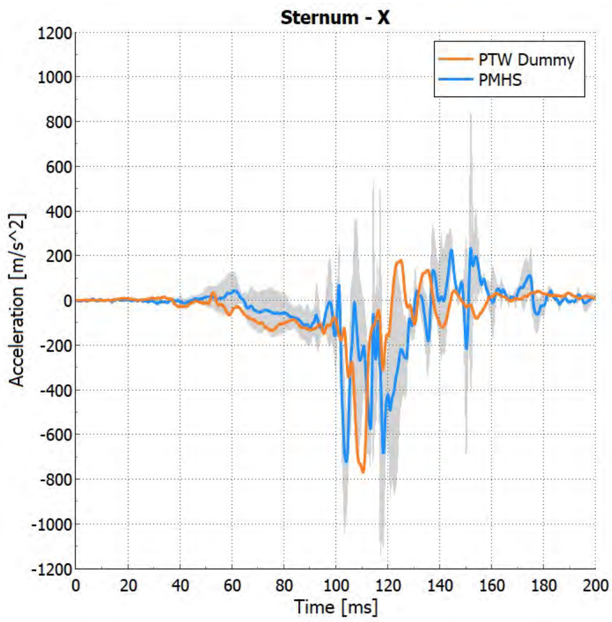

Fig. 10. Sternum linear acceleration in the x-axis, comparison of PTW Dummy and PMHS responses.

The thorax was also instrumented around the T4 level, at the rear of the body. The resultant linear accelerations, as well as the components from x-, y- and z-axes are shown in Fig. 11. Certainly, this figure indicates that the acceleration seen by the chest of the PTW Dummy had a slightly smaller peak value from contact with the car. Interestingly, the dummy acceleration exceeds 100 m/s^2 before the PMHS mean response (in the period prior to car contact), but is later in reaching 300 m/s^2 (when the car side contact is made). The PMHS all showed a rise to this level before 100 ms, receiving a more prolonged duration of loading as well. The CORA rating for the resultant channel was 0.78 (it was 0.56, 0.64 and 0.77 for x-, y- and z-axes, respectively).

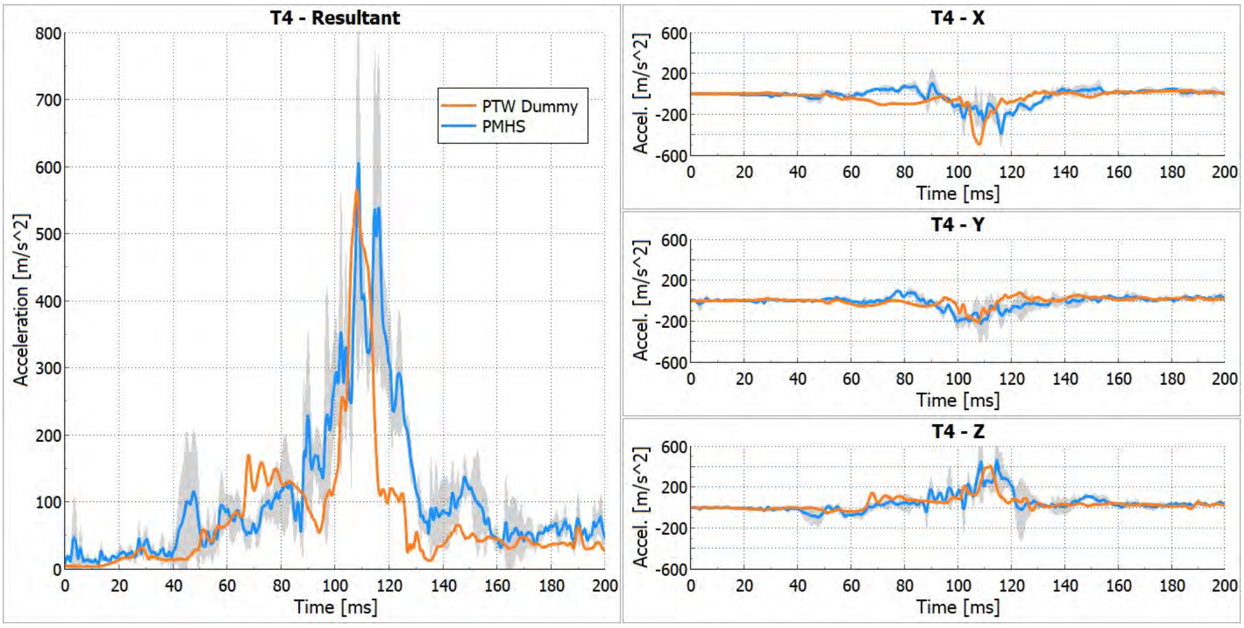

Fig. 11. Thoracic spine resultant linear acceleration comparison of PTW Dummy response and PMHS (x-, y- and z-axis components on the right).

Other instrumentation (points of interest)

Even though there is no corridor for the head accelerations, it was possible to compare the PTW Dummy data with the data available from two of the three PMHS tests. This is shown in Fig. 12, identifying the effect of the earlier engagement of the PTW Dummy head with the car and the higher acceleration coming from the roof-rail compared with the roof. Using a standard CORA comparison, the rating for the resultant head acceleration was 0.50 (it was 0.34, 0.56 and 0.43 for x-, y- and z-axes, respectively).

The HIC (Head Injury Criterion value) was 1564 for the PTW Dummy, in this test. It was 587 for PMHS Test 2 and 273 for PMHS Test 3.

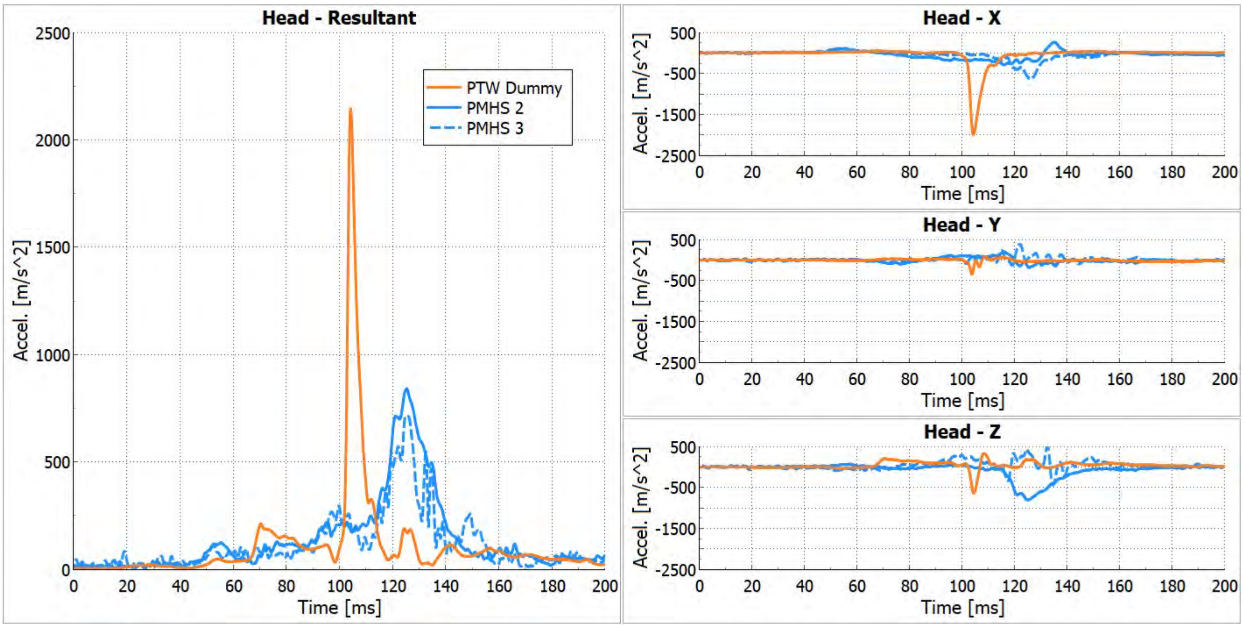

Fig. 12. Head resultant linear acceleration, comparison of PTW Dummy response and PMHS corridor.

The outputs of the lumbar load cell in the PTW Dummy have no direct relative in the PMHS, though some insights are interesting from that sensor too (Fig. 13, shown with a CFC600 filter according to SAE J211). There is some shear force on the PTW Dummy, particularly when impacting the car, but there is even more tensile force (more than 3 kN) between the time of pelvis contact with the fuel tank of the motorcycle and that of upper-body contact with the car. The bending moment also suggests substantial flexion during that time window (approximately 60–100 ms). Here it is noted that all the PMHS sustained an injury at the level of T11 in the spine.

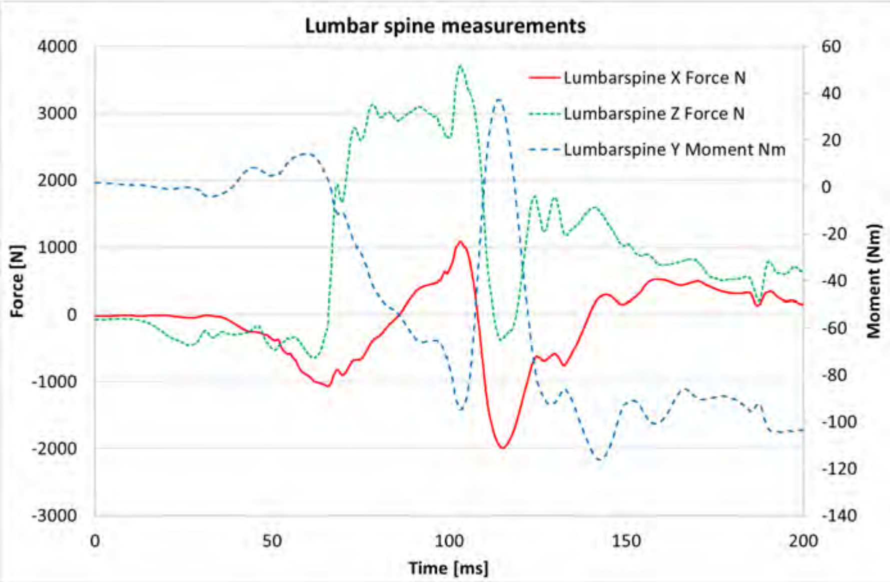

Fig. 13. Lumbar spine load cell responses from the PTW Dummy.

IV. DISCUSSION

It is difficult to set the performance of the PTW Dummy into any context regarding its biofidelity in this loading condition, given the absence of any prior observations with ATDs. Certainly, dummies have been used in PTW test series before (e.g. [20]) and their kinematics used to define the motion of riders during impact. The behaviour of a dummy and the resulting injury prediction metrics are the basis of the ISO Standard (13232 [21]) for the testing and analysis for research evaluation of rider crash protective devices fitted to motorcycles. Typically, the trajectories from motorcycle crashes with the side of a passenger car have indicated that the head of a dummy rider “continues to move almost horizontally along former travel direction until it hits the roof rail” [22]. This behaviour rarely seems to have been questioned, even though ‘ejection’ rather than ‘non-ejection’ kinematics for riders have been used in epidemiology studies for a long time [23].

For the first time, there are human responses in the same impact condition as the dummy test which set a useful precedent for future comparisons. That is not to say PMHS tests have not been performed on PTWs before, they have [24]. Indeed, those tests were used subsequently as a baseline to investigate the potential for protective padding to protect in the pelvis to fuel tank contact [25]. However, in that case the resulting sled test procedure was tuned to give an overall behaviour of the pelvis rather than concentrating exclusively on the biofidelity of the rider substitute.

Comparison with PMHS behaviour

In this test, the PTW Dummy rider’s pelvis did not recreate the acceleration profile of the PMHSs. The dummy does not allow for anticipated failures in the pelvis structure (and it did not break), and the pelvic ring underwent severe disruption in each PMHS test. Furthermore, the Hybrid III pelvis has never been tuned for interactions in the pubic region, so the stiffness of shallow foam over metal pelvis may well be different from the human soft tissue, bone and pelvic contents. A further limitation may be in the friction between suit and fuel tank, both over the inner thighs and the front of the pubis. The culmination of these factors resulted in the dummy pelvis sustaining a higher (500 m/s^2) peak deceleration than the PMHS (300 m/s^2), with more x-axis loading into the dummy pelvis. Here it can be noted that the cars used in the PMHS tests and PTW Dummy test were not the same model (either the US or European variant of the Honda Accord from 2011), the interactions with the motorcycle were not identical and the deformation of the motorcycle front structures and subsequent failures were not a perfect match. Nevertheless, the motorcycle accelerations were almost identical in the first 20 ms, and generally more closely related than the pelvis accelerations. Hence, it seems that the test differences would not account for the difference in pelvis to motorcycle interactions.

The pelvis is connected to the upper body via the lumbar region and in the PTW Dummy this means, exclusively, the lumbar spine. Whilst shear and bending moments were significant, the results also demonstrated 3 kN of tension at the base of the lumbar spine in the dummy. The lumbar and thoracic spine of the dummy cannot extend beyond their nominal lengths, so this force directly limits the potential excursion of the upper body. This centripetal pull towards the pelvis was not so evident in the PMHS where straightening and potential extension of the spine appears to have allowed for more horizontal translation of the upper thorax and head until contact with the car side.

Regardless of this, each subject was exposed to substantial loading to the front, upper part of the thorax. Sternum accelerations were over 600 m/s^2 in every test, and there were sternum fractures in the PMHS. The resultant acceleration at the back of the thorax reached a peak value for the dummy in the spine box at about the same time as in PMHS at the T4 vertebra, though the PMHS had a higher peak and longer duration of acceleration than the dummy.

It should be noted that there were many rib fractures in the PMHS, whereas no breakage was observed in the dummy chest and it recorded only 6 mm of deflection. Sensitivity of the rod potentiometer in the chest of the PTW Dummy to location and direction of loading may account (to some extent) for the small deflection measurement; but a 0.5% risk of serious injury contrasts starkly with the numerous rib fractures caused in the PMHS and the AIS3+ thoracic injuries in all three tests. It seems that both biofidelity and sensitivity are contributing to this underestimation of thoracic injury risk.

The most obvious external observation of the effect coming from the pelvis retention and transmission of force through the spine is in the motion of the PTW Dummy head with respect to the PMHS. In the case of the dummy, the face of the helmet (the chin bar) contacted the roof-rail of the car; whereas the PMHS heads did not.

Implications and potential

Based on this test configuration there are two critical areas where protective systems would be expected to influence the outcome, with two different implications coming from the dummy biofidelity: the head and the chest. In the case of serious head injuries, the PTW Dummy is predicting severe loading to the facial area through the helmet. To respond to this, safety engineers might try to intervene with a protective system [26], and this could be a conservative measure given the lack of any head injury in this configuration when testing with PMHS. Conversely, the dummy predicts little risk of serious injury to the thorax. This presents a problem for the protective concepts, as there is no challenge for protecting the dummy and no way of demonstrating a benefit in dummy-based crash tests. We know that the PMHS sustained serious thoracic injuries in this test condition and that upright PTW crashes can cause chest injuries in the field [27]. Therefore, it seems that this mismatched estimation of PTW Dummy risk to observed human risk is an issue for potential future safety systems that could protect the thorax.

Without a hard PMHS head to car contact, it is not possible to comment on the behaviour of the PTW Dummy in configurations that would generate such priorities for protection. Here we can only express the concern over the chain in kinematics up to the point of contact with the target vehicle. To study head contacts in the human, then a different experimental setup would be needed in equivalent PMHS tests and this subsequent research could form the basis for additional insights into the dummy biofidelity, perhaps the derivation of relevant component-level test requirements, and ideally then more specific head protection countermeasures. Simply changing the saloon car (sedan) for a higher-sided SUV, crossover car, pickup etc. as the target vehicle could be adequate to generate a head to vehicle injury mechanism with PMHS and would also represent diversity in the vehicle fleet. However, whilst such an approach should help to support more robust countermeasure designs, it has not yet been incorporated in ISO 13232 where only a passenger car, such as either of the Honda Accord models used here, is required and all impact testing features the MATD.

Adding alternative instrumentation to the thorax may improve sensitivity of the PTW Dummy to loading away from the x-axis or from the rod potentiometer attachment point. This would be important for capturing the severity of loading to the dummy's chest. However, the extent of loading seen in the PTW Dummy spine box was less (shorter duration) than that observed at the PMHS T4 vertebrae. Therefore, increased sensitivity would not address the underlying issue, which comes from the kinematics and the way the PTW Dummy thorax is presented to the car side. Further modifications would be needed to improve the biofidelity of the whole-body response, if the intention is to replicate thoracic loading in this test condition. Though not yet demonstrated, these observations may also affect the other crash test dummies which use the same composition from pelvis to neck (i.e. the MATD and the unmodified Hybrid III).

At this point, two key contributing aspects are recommended for further investigation. One is the compliance of the pelvis during the initial loading, and the potential need to represent failures to ensure later kinematics are matched. The other is the elongation of the spine – again with the question over the need to offer extension to match the PMHS behaviour better. Here it can be noted that predicting injury risk in the pelvis and thoracic spine could be important additions too, given their influence on the overall severity assessment for the PMHS. It is not clear if the pelvis acceleration and lumbar spine loads are adequate for this, without dedicated injury mechanism investigations. The feasibility of additional instrumentation in these regions could also be questioned in another step with the dummy development. In summary, the ideal test tool for protective system assessments would provide kinematics that challenge the needs for body retention and injury predictors that provide a challenge for energy management or protective load distribution, or both. It may be that these biofidelity and sensitivity requirements are better addressed with a Human Body Model, in which case, the PTW Dummy could still be a vital tool in validating simulation environments, but its use should be moderated based on the observations in this study and other relevant, future, evaluations. For instance, there has been no assessment of repeatability and reproducibility with the PTW Dummy yet, and no directly relevant information for the other PTW riding candidates, either.

One limitation of using a physical dummy to represent a few human subjects is that there is no opportunity for scaling to match anthropometry. Indeed, whilst efforts were taken to try and match sitting positions, the dummy could not be positioned precisely like any one of the PMHS. The interactions between the body and the car coming through, for instance, the knees, chest and head may be sensitive to differences in setup and sitting posture. This presents two further caveats for the conclusions from this work: first, that a different positioning approach might create different rider kinematics and hence potentially a different impression of PTW Dummy biofidelity – for instance, in an aggressive forward leaning posture where the head is certain to hit the car-side, and secondly, that handling of both PMHS and PTW Dummy could be improved with a defined positioning procedure or at least a stated 'humanlike' riding posture target. It is understood that this ambition to document how riders sit on a PTW (of various styles) is an ongoing research initiative [28], hopefully translating to practical guidance for test setups in the future.

V. CONCLUSION

A test with the PTW Dummy has been conducted reproducing the test conditions from full-scale, whole-body PMHS tests with a motorcycle crashing into a car. The reproduction in another test facility was not a perfect replica of the original tests, but already offers the potential to consider gross similarities and differences between the PTW Dummy and the PMHS. As such, we commend the usefulness of the original PMHS testing and corridors as a basis of such explorations into the suitability of test tools for potential safety system investigations.

Superficial observations show a consistent interaction of motorcycle to car, rider to motorcycle and then rider to car. However, from the pelvis-to-fuel tank contact onwards, differences emerged leading to the head of the dummy, as opposed to the chest of the PMHS, interacting with the roof-rail of the car.

Use of the PTW Dummy in common crash configurations like this front-of-the-motorcycle into the side-of-the-car case could underestimate the threat of thoracic injury. This would negate benefit estimates for systems that protect the chests of motorcycle riders in car collisions. These important observations regarding the biofidelity of the PTW Dummy with respect to the PMHS reference data thereby serve to guide potential users of the dummy as to its biofidelity in this test condition, and to its strengths and limitations in evaluating potential safety systems.

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VII. REFERENCES

[1] Backaitis, S. H. and Mertz, H. J. (1994) *Hybrid III: The First Human-Like Crash Test Dummy. Society of Automotive Engineers, Inc. (SAE),* Warrendale, PA, U.S.A.

[2] Foster, J. K., Kortage, J. O., Wolanin, M. J. (1977) Hybrid III – A Biomechanically-Based Crash Test Dummy. *Proceedings of the 21st Stapp Car Crash Conference*, 1977, New Orleans, Louisiana, U.S.A.

[3] Philippens, M., Cappon, H., *et al.* (2002) Comparison of the Rear Impact Biofidelity of BioRID II and RID2. *Proceedings of the 46th Stapp Car Crash Conference,* 2002, Ponte Vedra Beach, Florida, U.S.A.

[4] Hynd, D. (2007) "EEVC WG12 Rear Impact Biofidelity Evaluation Programme (HR-10-09e)", https://unece.org/DAM/trans/doc/2007/wp29grsp/HR-10-09e.pdf. [November 2007, accessed 6 February 2023].

[5] Yamazaki, K., Ono, K., Ishii, M. (2008) Biofidelity of Rear Impact Dummies in Low-Speed Rear-end Impact - Comparison of rigid seat and mass-production car seat with human volunteers. *Proceedings of the IRCOBI Conference,* 2008, Bern, Switzerland.

[6] Cesari, D., Compigne, S., *et al.* (2001) WorldSID Prototype Dummy Biomechanical Responses. *Proceedings of the 45th Stapp Car Crash Conference,* 2001, San Antonio, Texas, U.S.A.

[7] Damm, R., Schnottale, B., Lorenz, B. (2006) Evaluation of the Biofidelity of the WorldSID and the ES-2 on the basis of PMHS data. *Proceedings of the IRCOBI Conference,* 2006, Madrid, Spain.

[8] Rhule, H., Moorhouse, K., Donnelly, B., Stricklin, J. (2009) Comparison of WorldSID and ES-2RE biofidelity using an updated biofidelity ranking system. *Proceedings of the 21st International Technical Conference on the Enhanced Safety of Vehicles Conference (ESV),* 2009, Stuttgart, Germany.

[9] Kim, T., Shaw, G., *et al*. (2016) Biofidelity evaluation of WorldSID and ES-2RE under side-impact conditions with and without airbag. *Accident Analysis and Prevention*, **90**(May 2016): pp. 140–151.

[10] Shaw, G., Crandall, J., Butcher, J. (2000) Biofidelity evaluation of the THOR advanced frontal crash test dummy. *Proceedings of the IRCOBI Conference,* 2000, Montpellier, France.

[11] van Don, B., van Ratingen, M., *et al.* (2003) Evaluation of the Performance of the THOR-Alpha Dummy. *Proceedings of the 47th Stapp Car Crash Conference,* 2003, San Diego, California, U.S.A.

[12] Parent, D., Craig, M., Moorhouse, K. (2017) Biofidelity evaluation of the THOR and Hybrid III 50th Percentile Male Frontal Impact Anthropometric Test Devices. *Proceedings of the Stapp Car Crash Conference,* 2017, Charleston, SC, U.S.A.

[13] Hagedorn, A., Stammen, J., *et al.* (2022) Biofidelity Evaluation of THOR-50M in Rear-Facing Seating Configurations Using an Updated Biofidelity Ranking System. SAE International Journal of Transportation Safety, **10**(2): pp. 291–375.

[14] St-Laurent, A., Szabo, T., Shewchenko, N., Newman, J. A. (1989) Design of a Motorcyclist Anthropometric Test Device. *Proceedings of the Twelfth International Technical Conference on Experimental Safety Vehicles (ESV),* 1989, Göteborg, Sweden.

[15] Newman, J. A., Zellner, J. W., Wiley, K. D. (1991) A Motorcyclist Anthropometric Test Device MATD. *Proceedings of the IRCOBI Conference,* 1991, Berlin, Germany.

[16] Carroll, J., Been, B., Sundmark, H., Burleigh, M., Li, B. (2022) A Powered Two-Wheeler Crash Test Dummy. *Proceedings of the IRCOBI Conference,* 2022, Porto, Portugal.

[17] Carroll, J, Been, B., Burleigh, M. (2023) A novel powered two-wheeler rider dummy; specifications and initial testing. *Proceedings of the 27th International Technical Conference on the Enhanced Safety of Vehicles (ESV),* 2023, Yokohama, Japan.

[18] Van Meter, M., Carroll, J., *et al.* (2023) Development of Powered Two-Wheeler PMHS Crash Test Methodology. *Proceedings of the IRCOBI Conference,* 2023, Cambridge, U.K.

[19] Pipkorn, B., Larsson, K.-J., *et al.* (2018) Occupant Protection in Far-Side Impacts. *Proceedings of the IRCOBI Conference,* 2018, Athens, Greece.

[20] Brun-Cassan, F., Vincent, J. C., Fayon, A., Tarriere, C. (1984) Investigation of a series of representative experimental collisions between automobiles and two-wheeled vehicles with specific analysis of severity of head impacts. *Proceedings of the IRCOBI Conference,* 1984, Delft, The Netherlands.

[21] ISO (International Organization for Standardizarion) (2005) *ISO 13232: Motorcycles - Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles.* ISO, Geneva, Switzerland.

[22] Schaper, D. and Grandel, J. (1985) Motorcycle collisions with passenger cars - analysis of impact mechanism, kinematics, and effectiveness of full-face safety helmets. *SAE Transactions*, **94**(1): pp. 544–581.

[23] Hight, P. V., Siegel, A. W., Nahum, A. N. (1976) Injury mechanisms and motorcycle design. *Proceedings of the IRCOBI Conference,* 1976, Amsterdam, The Netherlands.

[24] Serre, T., Masson, C., *et al*. (2019) Airbag jacket for motorcyclists: Evaluation of real effectiveness. *Proceedings of the IRCOBI Conference,* 2019, Florence, Italy.

[25] Whyte, T., Koudounas, V., *et al*. (2020) A physical test method to evaluate pelvis protection for motorcyclists. *Proceedings of the IRCOBI Conference,* 2020, planned for Munich, Germany (postponed).

[26] Meng, S., Gowda, S., Lubbe, N. (2022) The face airbag: a novel concept for facial impact protection. *Proceedings of the IRCOBI Conference,* 2022, Porto, Portugal.

[27] Carroll, J., Gidion, F., Rizzi, M., Lubbe, N. (2022) Do motorcyclist injuries depend on motorcycle and crash types? An analysis based on the German In-Depth Accident Study. *Proceedings of the 14th International Motorcycle Conference,* 2022, Cologne, Germany.

[28] Lundin, L., Oikonomou, M., *et al.* (2024) Quantifying Rider Posture Variability in Powered Two and Three-Wheelers for Safety Assessment. *In Press.*