Ability of Human Body Models to Represent Injury Patterns Observed in PMHS Tests and Field Data

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Abstract Human body models (HBMs) are increasingly used to investigate possible injury mechanisms and restraint system performance. Previous work has shown discrepancies between rib fracture distributions reported in PMHS sled tests and those observed in field data, with hypotheses suggesting a stronger role of lower torso and pelvis excursion in real-world thoracic injury. In this study, HBM simulations were performed to examine whether these reported trends can be reproduced numerically. Simulations were conducted in rigid sled environments representing published PMHS test configurations with varying airbag and knee restraint conditions, as well as in a total vehicle environment with varying impact speed and knee-restraint conditions. It was found that while the simulated rib fracture distributions do not closely match those reported in the literature, HBMs were able to consistently reproduce trends linking increased pelvis excursion with simplified experimental setups. Full vehicle simulations exhibit systematically higher pelvis excursions than PMHS-based sled simulations at comparable impact speeds. These findings suggest that HBMs can capture key kinematic differences hypothesised to contribute to discrepancies between PMHS and field injury patterns, although substantial limitations remain in predicting the number and location of rib fractures.

Keywords *Crashworthiness, Frontal crashes, HBM, PMHS, Thoracic injury.*

I. INTRODUCTION

In Brumbelow's [1] comparison between PMHS data to field data, discrepancies were reported in both the number and location of the observed rib fractures. It was noted that the largest differences in observed rib fracture outcomes related to the presence of an airbag or a knee restraint. It was also noted that these restraints would have associated consequences on the kinematics. Specifically, the presence of the airbag would cause less torso pitching, but more lower extremity excursion, whereas a knee restraint would see less lower extremity excursion and more upper torso pitching. Several other publications were referenced which supported the findings that increases in lower extremity excursion are associated with higher level of thoracic injury [4–7].

Therefor the main question posed in this work is to see if by using HBMs the kinematic differences associated with both PMHS tests as well as real-world crashes can be reproduced.

To achieve this a study is proposed in three steps:

The first step was to reproduce the rib fracture patterns observed in the PMHS data findings first reported by [1] using HBM simulations in sled test environments which accurately reflect the PMHS test conditions.

The second step of the study was to use HBM models in a full vehicle crash environment to approximate the trends reported which describe the field data.

The third step is to compare the thoracic injury indicators and lower extremity excursions using between the conditions investigated in steps one and two

II. METHODS

Simulation Study Comparing HBM Responses to Reported PMHS Responses

The data in the original study are both detailed and varied, mainly drawing on the NHTSA biomechanics database as the main source for PMHS injury data [8]. As one of the main conclusions in [1] was that the presence of airbags and knee restraints have the largest impact on the thoracic injury outcomes, the focus of the first phase simulations was to investigate the effects of these two restraint systems.

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The sled test case selected to investigate an airbag restraint is the open-source Lopez-Valdez 2017 load case from the HBM4VT repository [9]. This load case recreates the tests performed by Lopez-Valdez *et al.* [10] in which a rigid sled undergoes a 35km/h pulse, where the PMHS are restrained by both an airbag and a seatbelt with a load-limiter. All simulations were performed with an unmodified THUMS v4.1 model [11].

Four conditions were simulated: Restraint Condition A was characterised by the airbag being pre-inflated to a pressure of 16kPa and the load limiter being set to 2.5kN. Restraint Condition B had an airbag pressure of 11kPa and a load limiting force of 2kN. The final two load conditions correspond to conditions A + B, but for these load cases the airbag has been removed and are then signified as Conditions A_noAB and B_noAB. These two final conditions are artificial cases only used to generate synthetic data to attempt to resolve the airbag effectiveness and were never performed using PMHS. An example of the simulation setups look can be seen in Fig. 1.

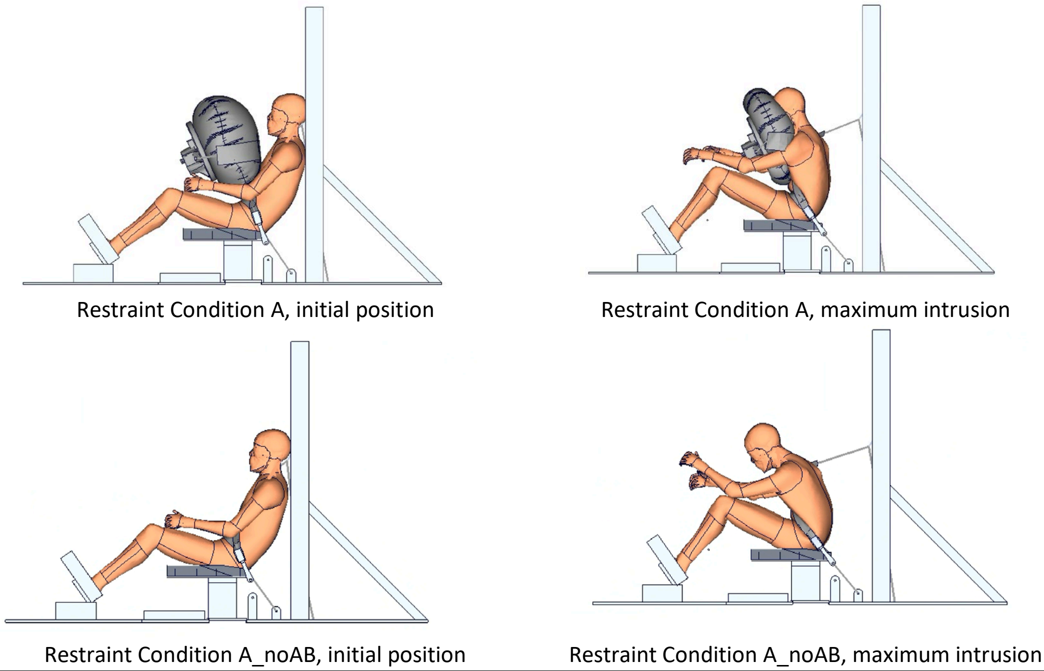


Fig. 1: Visualization of the various simulation conditions for the Lopez-Valdez 2017 validation load case.

The resulting strains were then evaluated using the THUMS v4.1 tuned rib risk injury curve presented by Forman *et al.* [12]. For this study a fractured rib is counted as a rib where the risk is greater than 50%. The 50% threshold was chosen as this is the point where fractures are more likely to occur than not. The was done in order to have comparable counts to what was previously reported in [1], instead of the probability distributions in the original derivation [12]. The resulting fractures and their distribution across the ribcage were compared to the previously reported study [1].

A second load case was also simulated analogously to the first but in which the presence of a knee restraint was the variable in question. For this case, the Shaw *et al.* 2009 “Gold Standard” [13] test series was simulated, also by using the open-source model provided by HBM4VT [9]. Four conditions were simulated. All setups consist of the same rigid seat, with an unmodified THUMS v4.1 being used as the HBM. The Gold Standard 1 (GS1) setup is comprised of a 40km/h pulse with no load limiter. The Gold Standard 2 (GS2) setup uses a 30km/h pulse with a 3kN load limiter. Two additional conditions corresponded to GS1 and GS2 with the knee restraint removed, referred to as GS1_noKR and GS2_noKR, respectively were also investigated. The two conditions with the restraint removed are purely simulation studies, and do not reflect the original experiments. These simulations were performed to generate additional synthetic data to better compare results. Visual examples of this setup can be seen in Fig. 2.

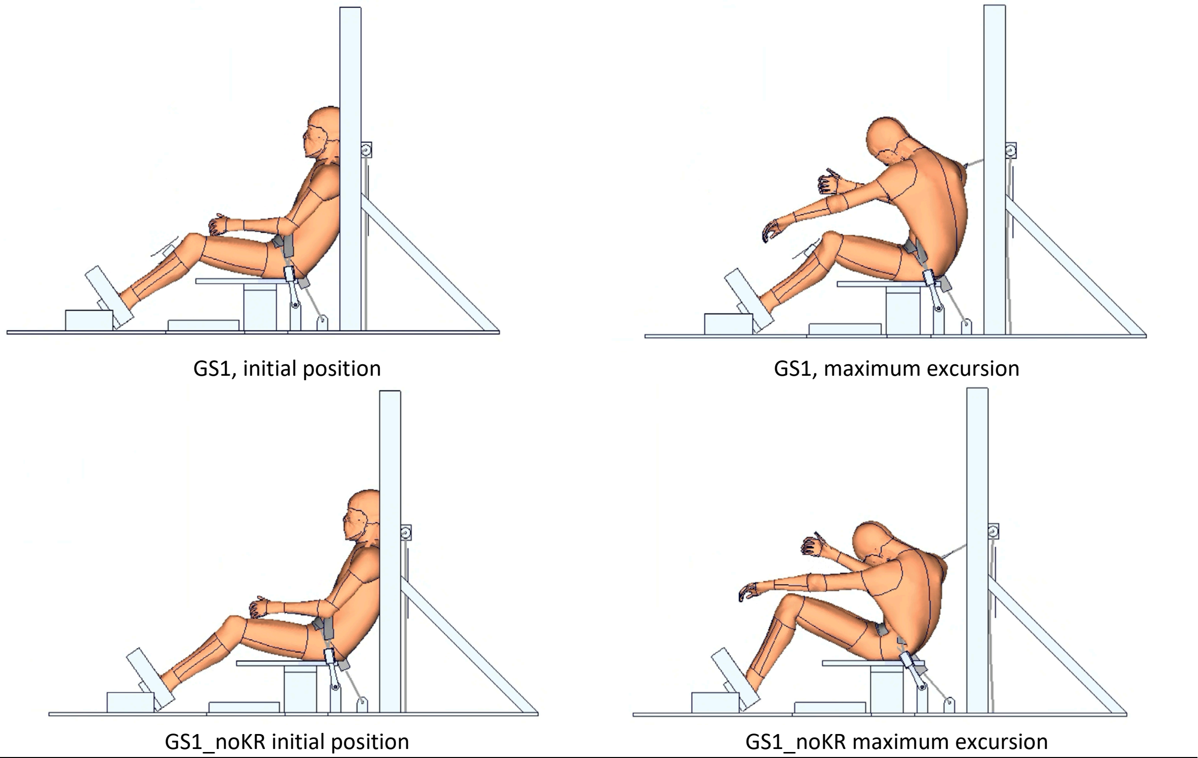


Fig. 2: Visualisation of the various simulation conditions for the Shaw 2009 validation load case.

As with the Lopez-Valdez simulations, the resulting rib strains are used to calculate rib fracture risks and the number and location of the fractures is compared with the reported data.

Simulation Study comparing HBM Responses in a Full Vehicle Environment to Field Data

In order to represent the field data, simulations were run using the THUMS v4.1 in the generic NHTSA Honda Accord model [14].The vehicle was subjected to a full-frontal impact against a rigid barrier, with varying impact velocities, ranging from 30km/h to 60km/h. Additionally, the simulations were run in a default configuration, and in a configuration where the structural components associated with knee contact were removed. A representative simulation can be seen in Fig. 3.

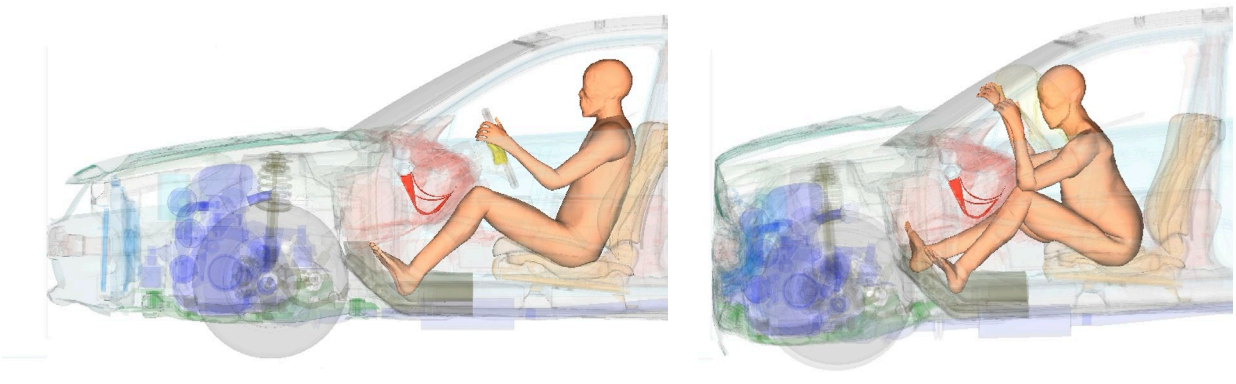


Fig. 3: NHTSA Honda Accord full frontal rigid barrier load case. The knee restraint components highlighted in red.

The resulting rib strains for each varying impact velocity and restraint condition were used to calculate rib fracture risks. As a proxy for the lower extremity excursion, pelvis displacement relative to the environment was plotted, and the maximum taken as the representative measure.

Ability of HBMs to Differentiate between PMHS Tests and Field Data

The third and final part of the study concerned the ability of HBMs to test hypotheses regarding differences in PMHS tests and field data. The main hypothesis to be tested is that:

"The difference in PMHS rib fracture locations by restraint condition suggests real-world rib fractures are more strongly associated with excursion of the lower torso and pelvis than with forward pitch of the torso" - Matt Brumbelow, *Identifying thoracic injury factors by comparing rib fracture patterns in field crashes and PMHS sled tests.*

The objective was therefore to test if HBMs can reproduce the differences in lower extremity excursions and thoracic injuries associated with both PMHS test and real-world crashes.

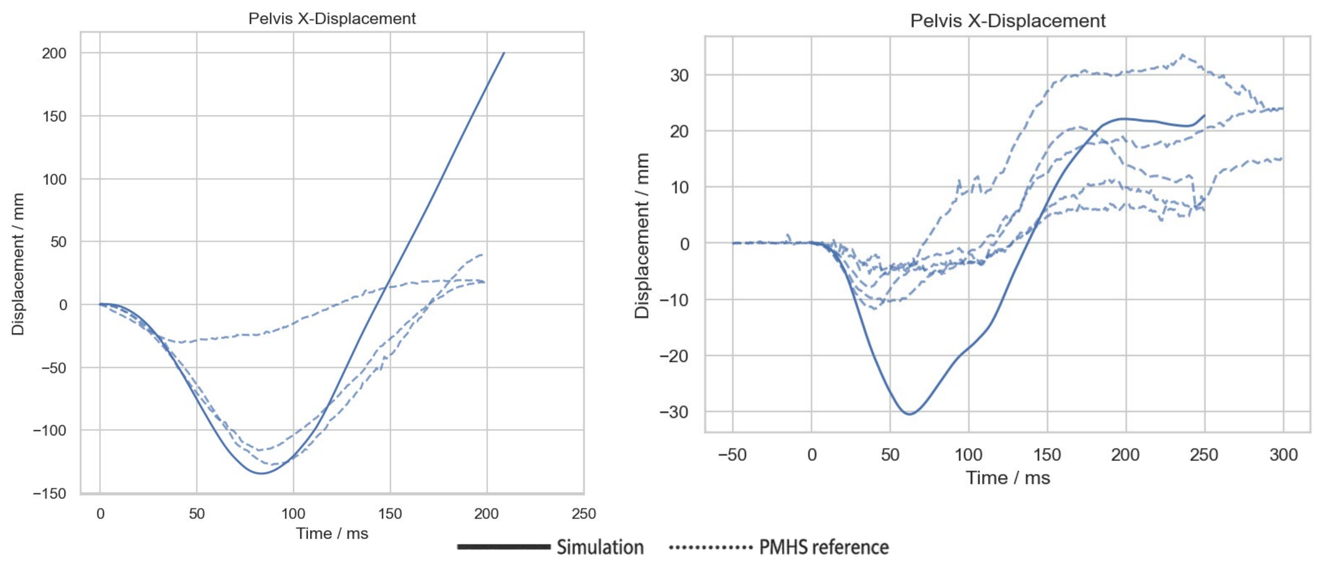
In order to test this hypothesis, the sled simulations as described above were analysed. This full vehicle model represents the field data kinematics and injury outcomes. The distributions of the number of fractured ribs as well as the differences in the number of broken ribs in paired configurations were also analysed.

III. RESULTS

Simulation Study Comparing HBM Responses to Reported PMHS Responses

The inherent complexity of using HBMs to validate PMHS test is out of the scope of this paper, so instead the ability of HBMs to reproduce PMHS behavior will be investigated only for the pelvis displacements and the rib fractures observed.

For the pelvis displacement in the direction of the crash pulse, the HBM4VT Project readily provides a template for the calculation of the pelvis displacement corridors [9], as shown in Fig. 4. These displacements are only in the x-direction.



Lopez Valdez Restraint Condition A   Gold Standard 2

Fig. 4: Pelvis displacement corridors for the PMHS validation simulations, taken from [9]. Solid lines represent simulation test data, dotted lines are PMHS test reference data.

Concerning the number of rib fractures, the number of reported fractures from the literature can be compared with the fractured ribs calculated from the HBM simulations, presented in Table 1.

Table 1: Comparison in the number of observed rib fractures between PMHS and HMB

	PMHS	HBM
Lopez-Valdez A	10-15	0
Lopez-Valdez B	0-4	0-1
Gold Standard 1	5-17	0-4
Gold Standard 2	0-7	0

In order to see if any dependencies are apparent between the pelvis displacement and the number of rib fractures, a scatter plot is presented in Fig. 5.

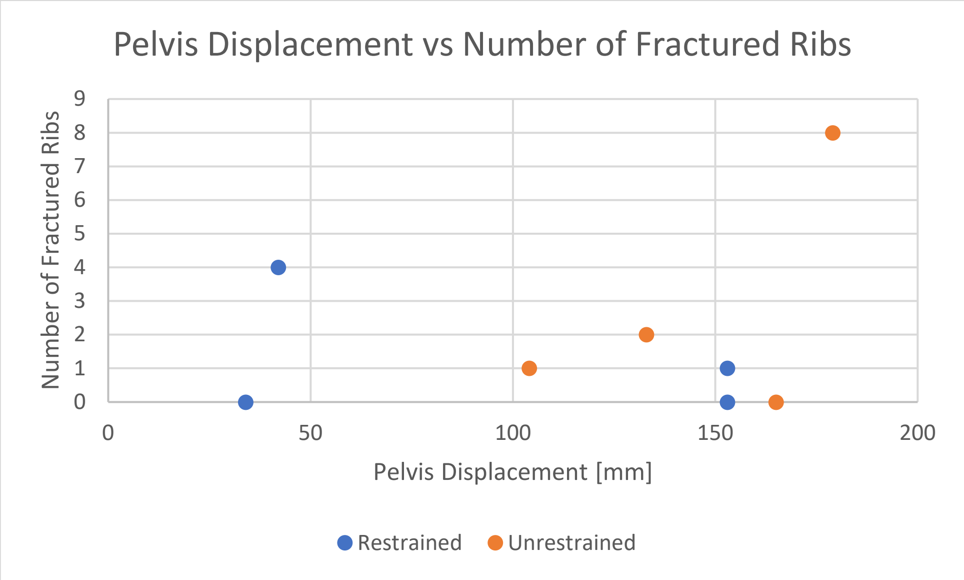
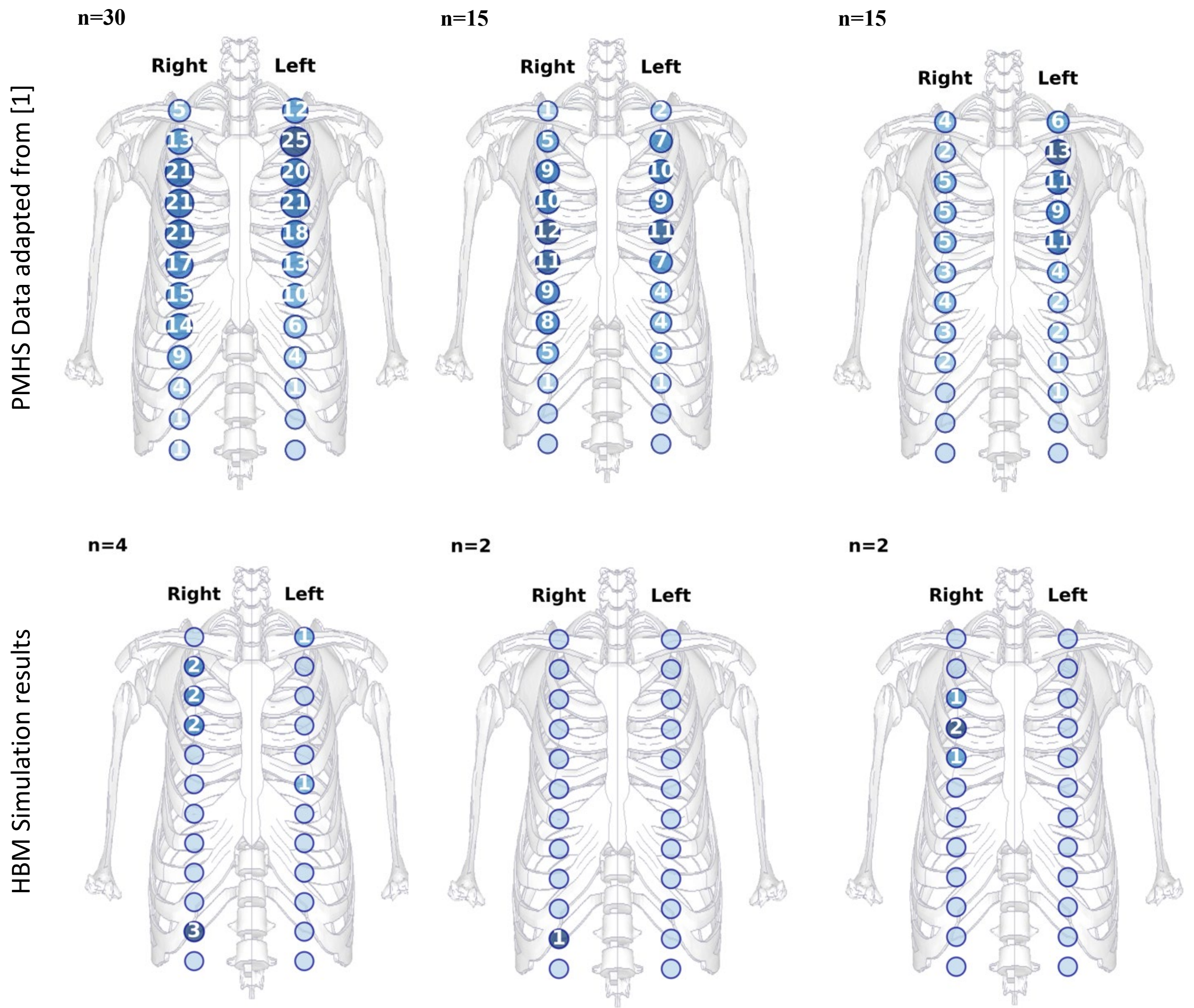


Fig. 5: Number of rib fractures as a function of pelvis displacement for the PMHS validation simulation, restrained refers to knee support for the Shaw 2009 simulations and to the airbag for the Lopez-Valdez 2017 simulations.



(a) Without airbag, without knee support (b) With airbag, without knee support (c) Without airbag, with knee support

Fig. 6: Distribution of rib fractures in the PMHS validation load cases. Plotted values correspond to the number of fractured ribs observed for each load case.

The small number of samples, and the limited number of configurations leads to a small overall number of observed fractures, and this makes comparing the observed distribution difficult: as with few data points any patterns observed cannot be resolved to a very fine degree. The resulting rib fracture distributions, evaluated in a manner consistent with [1] are shown in Fig. 6.

Simulation Study comparing HBM Responses in a Full Vehicle Environment to Field Data

For the field data there is no direct measure of either the pelvis displacement or the number of fractured ribs. To the authors' knowledge field data concerning pelvis displacement does not exist at a level sufficient to make detailed comparisons, as it is a dynamically measured phenomenon. The number of rib fractures was estimated in [1] for colinear frontal crashes, as rib fractures can be counted after an accident event. A diagram prepared analogously but using rib fracture data from the full vehicle simulation study is shown in Fig. 7.

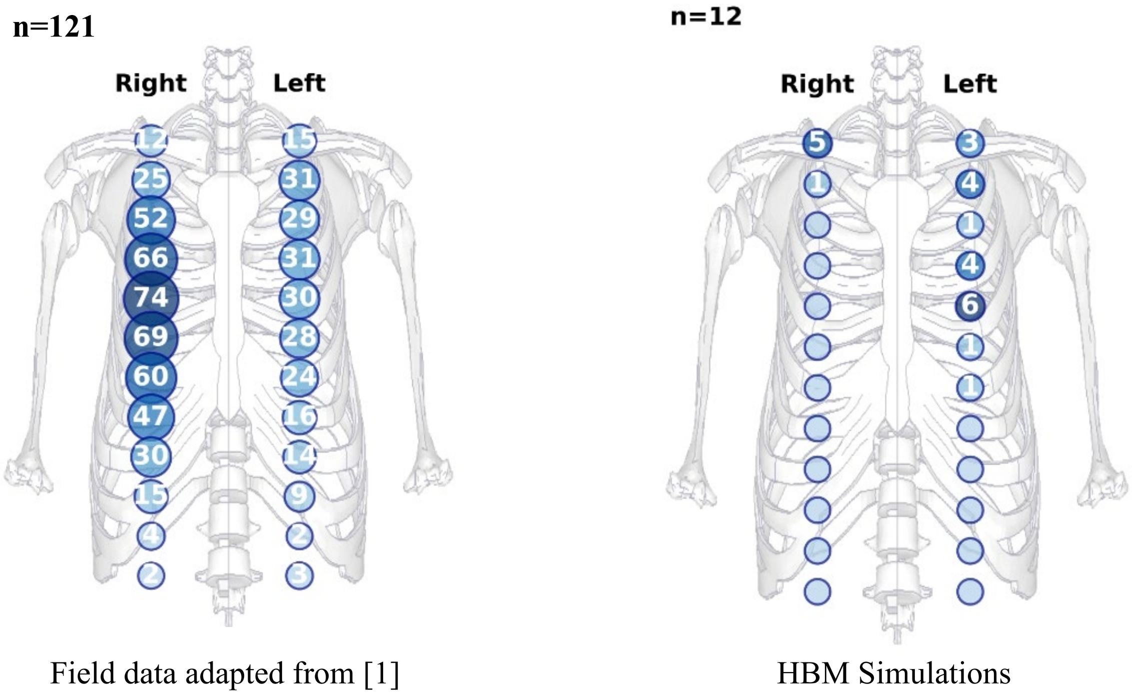


Fig. 7: Distribution of rib fractures from the full vehicle simulation study corresponding to field data.

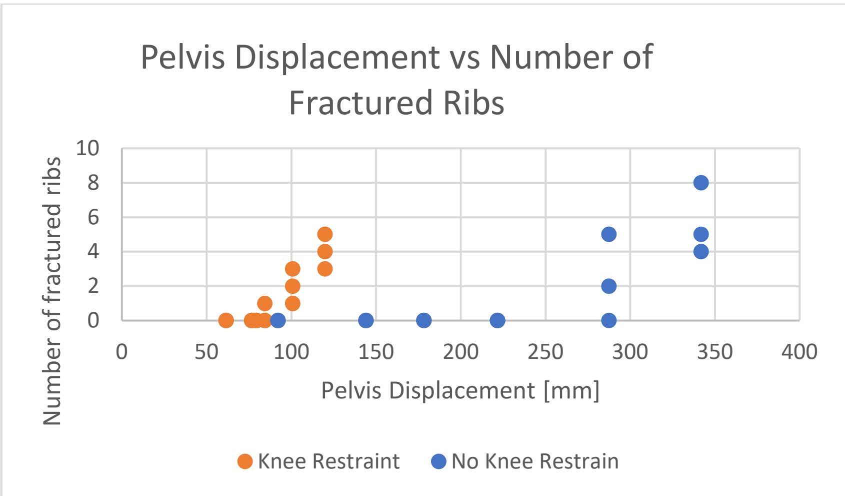


Fig. 8: Number of fractured ribs plotted against pelvis displacement for the total vehicle field data HBM simulations.

In order to investigate the relationship between pelvis displacement and number of rib fractures, a plot comparing rib fractures as a function of pelvis displacement for the full vehicle simulations is shown in Fig. 8.

Comparing the pelvis excursion to the risk of rib fracture directly, larger pelvis excursions correlate with higher numbers of fractured ribs inside of each load case cluster. The full vehicle condition with no knee restraint shows higher pelvis excursions than the full vehicle simulations with knee restraints. The two restraint conditions in the full vehicle simulations are distinctly clustered.

Ability of HBMs to Differentiate between PMHS Tests and Field Data

In order to better visualise the explanatory variables, the pelvis displacement was plotted against impact speed, see Fig. 9. For a given impact speed, the PMHS validation simulations have lower pelvis excursions than the corresponding full vehicle simulations. The uppermost PMHS validation simulations being those with no knee restraint are slightly below the full vehicle simulations with no knee restraint, and analogously the lower PMHS validation simulations with knee restraint are even lower than the full vehicle simulation with knee restraint.

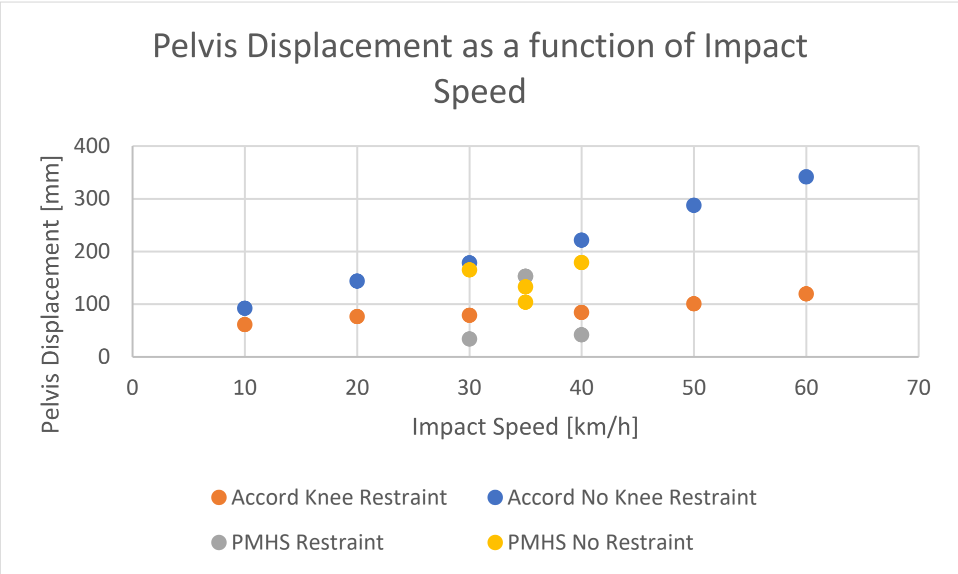


Fig. 9: Pelvis Displacement as a function of impact speed.

IV. DISCUSSION

Simulation Study Comparing HBM response to Reported PMHS Reponses

Comparing HBMs to the reference PMHS tests, the pelvis kinematics are in good agreement for the Lopez-Valdez case, but overestimate in the Gold Standard 2 load case. This overestimation of the pelvis displacement is still below what was observed in the full vehicle simulations at the same impact speed. If one assumes the full vehicle kinematics are accurate then the difference in reality should be even larger than what the HBM simulations show.

The number of rib fracture observed in the PMHS tests compared to the number reproduced in the simulations shows a poor agreement, with the HBM strongly underestimating the numbers of broken ribs. Until now most of the focus with HBMs has been kinematic based, and strain-based injury prediction and validation remains a challenge. However, only the THUMSv4.1 HBM was used in this study, and only two PMHS validation load cases were considered, which is a small sample with which to generalise. With the monitoring of strain-based criteria starting in 2026 and assessment planned for 2029 in the latest Euro NCAP protocols, more work will likely be required on this topic in the near future.

Regarding the distributions of the fractures, the small number of simulations used to try to represent the data presented in [1] is a large limitation of this study. The dataset from [1] contains 86 PMHS tests, in this study only eight simulations were performed, with the data supplemented by calculating risk for three separate ages. Compared with the results presented in [1], the simulations show fractures in locations not observed in the reference study. This could be due to the low number of tests investigated, or an artefact of THUMSv4.1, or even due to how this setup was modelled. Next steps should focus on simulating all the tests referenced to determine which areas need improvement for accurate fracture reproduction. It is also a limitation that the Lopez-Valdez experiments are not in the dataset in [1], but it is also unlikely that a single addition test setup would change the results in a significant manner.

Looking at the correlations between pelvis displacement and the number of fractured ribs, the PMHS- test simulations show a weaker correlation than the full vehicle simulations, which is likely due to their diversity. The pulse levels are in the same range for both sets of simulations, but for the PMHS validations different seatbelt load limiter configurations ranging from rigid belts to 2kN are expected to strongly influence the number of rib fractures, and indeed the largest number of rib fractures occur in the Gold Standard 1 configurations where no load limiters are present. The Gold Standard 1 simulations also have the highest impact velocities, the high energy of which surely contributes to the observed fractures.

There is also likely an influence due to the rigid or semi-rigid seat pan commonly used in PMHS test, as opposed to the fully deformable seats used to represent the field data. The deformable seats in general allow more pelvis rotation, as well as more forward displacement, but the influence of the knee restraint is much larger. Nevertheless the use of rigid seats is one explanatory factor to the differences observed in [1] between PMHS tests and field data which should be further investigated.

Simulation Study comparing HBM Responses in a Full Vehicle Environment to Field Data

The distributions of the rib fractures comparing the reported field data to the observed HBM fractures in full vehicle simulations do not match well. A separate study [2] has found that with more variation the HBM results more closely resemble the field data. These variations include deformable crash partners, impact and airbag activity. As the study here only considers rigid full-frontal crashes in only one restraint system configuration, divergence from real-world field dataset can be expected. The reason this smaller data is used instead of the larger one is to better compare to the PMHS sled tests, which most closely resemble full-frontal rigid barrier crashes.

In Fig. 5, positive correlations can be seen between pelvis displacement and number of fractured ribs in both restraint conditions, as well as for the PMHS validation cases. Higher numbers of fractured ribs are observed in the no-knee-restraint condition where the highest pelvis displacements are occurring, but with exceptions concerning the PMHS validation simulations, which is likely due to the different seatbelt load-limiter configurations used. That the positive correlation is stronger for the knee restraint case is due to the distribution of the lowest displacement pelvis excursions, which all result in no fractures. The two test variables implicitly present in this data set are the presence of a knee restraint, and the variation in impact speed, but only looking at the pelvis displacement vs. number of rib fractures results, neither speed nor restraint condition can be clearly seen in Fig. 5.

Ability of HBMs to Differentiate between PMHS Tests and Field Data

Figure 7 shows a very strong correlation between the pelvis displacement and impact speed. As the primary mechanism causing the displacement in the first place is the deceleration of the environment, this is consistent with previous findings [15-17].

For all given impact speeds, the pelvis displacement for the PMHS validation simulations is always lower than those seen in the total vehicle simulations. This is a positive finding, as this shows that the HBMs are able to predict the kinematic differences postulated to be a main explanatory factor towards the difference in rib fractures seen in PMHS tests and field data. This is, however, purely a function of the HBM kinematics, which until now have been more extensively validated than the injury prediction capabilities. Looking at the number of broken ribs, more work is still needed in order to have an adequate prediction and should be undertaken to not only predict the number of fractures, but also their locations. The restrained PMHS cases show less pelvis displacement relative to the restrained full vehicle simulations than the unrestrained PMHS cases relative to the unrestrained full vehicle simulations. This is a conservative finding, as most vehicles have some form of knee restraint. Combining this with the Shaw 2017 HBM simulations overestimation of the pelvis displacement, this delta becomes even larger, signifying that HBMs show strong signs of being able to differentiate pelvis kinematics in the real world vs. in rigid sled tests. This kinematic difference can then in turn be transferred into a difference in rib fracture outcomes.

There are confounding factors which remain as limitations. In this study the impact velocity is taken as a constant, where different vehicle sizes with the same delta-v can have very different pulses which act on the occupant. Similarly, it is not clear how the pulses used in the PMHS validation studies relate to the pulses in the full vehicle simulations; more work is needed to analyse this influence. This study was carried out using only the THUMS v4.1 and the open-source Honda Accord model provided by NHTSA, so more studies are needed to show if the findings presented here are generalisable to other HBMs and vehicle environments, which is ultimately necessary to conclusively prove or disprove the representability of PMHS kinematics to real-world thoracic injuries. The validation of the models in general as it relates to fracture also is a large limitation, in this study differences could be observed, but without sufficient validation, no objective conclusions about absolute levels of rib fracture risk can be made.

V. CONCLUSION

This study investigated the ability of HBMs to reproduce rib fracture patterns observed in PMHS testing and to evaluate hypotheses relating thoracic injury to lower-torso and pelvis excursion. When attempting to replicate reported PMHS rib fracture distributions, the simulated results showed limited agreement in both the number and location of fractures, but better agreement regarding pelvic kinematics. This highlights ongoing limitations in current strain-based rib fracture prediction methods and their sensitivity to model assumptions, boundary conditions, and subject variability, and availability of high-quality data needed for validation.

Future validation work could consider numbers of rib fractures as a validation criteria, but the low numbers of PMHS tests, as well as the wide variability of number of fractured ribs for a given setup needs more work. Extending the current stochastic approaches to address this could be promising.

Despite these limitations, consistent trends were observed across simulation environments linking increased pelvis excursion to increased rib fracture risk. This relationship was evident in both rigid sled simulations and full-vehicle frontal crash simulations, with the latter exhibiting higher pelvis excursions at comparable impact speeds. The systematic difference in the HBM pelvis excursion between PMHS-based sled environments and full-vehicle simulations supports the hypothesis that kinematic differences, rather than injury tolerance alone, contribute to discrepancies between PMHS and field rib fracture patterns, and shows that current HBMs are sensitive enough regarding their kinematics in order to capture this behavior.

Overall, the results indicate that while current HBMs are not yet able to accurately predict rib fracture distributions, they are capable of reproducing kinematic trends that are plausibly linked to real-world thoracic injury mechanisms. Further work is required to improve rib fracture risk prediction, including refinement of injury criteria, improved representation of restraint system variability, and broader validation across impact conditions and model types. Such developments are necessary before HBMs can be relied upon to predict not only injury trends, but also injury outcomes with sufficient accuracy for safety assessment applications.

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