Active Human Body Model Simulations of Whole-Sequence Braking and Far-Side Side-Impact Configurations

Jacob Wass, Jonas Östh, Lotta Jakobsson

Abstract Vehicle crashes may be preceded by evasive manoeuvres, executed by the driver or automatically. This study demonstrates a seamless simulation with an Active Human Body Model (HBM) as driver in a whole-sequence crash scenario, consisting of a braking intervention followed by a side-impact to the passenger side.

Ten simulations were run with two different side-impact configurations combined with two impact speeds. Possible effects of restraint intervention by a reversible seatbelt retractor and a far-side airbag function were studied, analysing displacements and tissue level injury predictions using the SAFER HBM.

The braking intervention led to a more forward occupant position at the start of the crash phase. A more forward impact point on the vehicle side resulted in 50 mm lowered lateral head excursion, compared to a mid-compartment impact configuration. This was influenced by the larger vehicle rotation and reduced lateral crash pulse.

The SAFER HBM was shown to be capable of seamless simulations combining a braking intervention followed by a far-side side-impact. This enables a larger range of possible real-world representative scenarios to be used for occupant protection evaluation, including both pre-crash and in-crash protection systems.

Keywords Human Body Model, Finite Element, Whole-Sequence, Far-Side, Active Muscle

I. INTRODUCTION

The development of Active HBMs [1-6], i.e. HBMs that incorporate modelling of occupant muscle responses, has enabled simulation of whole-sequence real-world-type crash scenarios that would be difficult to simulate or evaluate in testing with crash test dummies. Examples of whole-sequence scenarios are, for instance, an emergency braking followed by a frontal impact, steering, or combined braking and steering prior to front, side, or rear impacts [7]. Such pre-crash manoeuvres can displace the occupants from nominal driving or riding postures [8-9].

Previous studies have utilized two different methods to enable the simulation of a long (on the crash time scale) duration pre-crash manoeuvre, typically a braking preceding a frontal impact. In a number of studies [10-12], the authors used a sequential simulation strategy for which the Active HBM was used to simulate the pre-crash manoeuvre and then another HBM, with injury prediction capabilities, was used for the crash-phase. This method has benefits in that more numerically efficient models, of both HBM and vehicle interior [12], can be used for the pre-crash phase, but it introduces an intermediate pre-processing step as the Active HBM internal state and position needs to be transferred to the HBM used in the crash phase [12]. For instance, Yamada *et al.* [10] used the THUMS v5 with active muscles to simulate the occupant response to 1.1 g braking, and then transferred the occupant kinematics generated by the Active HBM to prescribed motions for the THUMS v4 prior to the crash, thereby reproducing both the initial position and the velocity of the occupant at the start of the impact. The authors reinitialized seatbelt forces but did not transfer muscle tension from the active model to the passive model. The study showed that a braking intervention which reduced the subsequent crash severity led to reduced maximum forward displacement and injury predictions for a small female, an average and large male, compared with no braking before crash.

The second method uses a seamless whole-sequence strategy in which both the pre-crash and the crash phase are simulated with the same HBM. The first Finite Element (FE) HBM shown capable of this was the SAFER HBM,

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in studies presented at IRCOBI in 2016 [13-14]. The authors demonstrated that an Active FE HBM can be used to help guide the design of active safety technologies and restraint systems activated prior to the impact, exemplified by auto-brake and an electrical reversible seatbelt retractor [13-14]. The advantage of using the Active HBM throughout the event is that the initial conditions for the crash are directly and completely recreated as there is no interruption of the simulation, and therefore muscle activations that could influence the outcome of the crash can be maintained [15-17]. In addition, no intermediate pre-processing step is needed, which simplifies the setup of simulation sequences. The drawback of the seamless simulation method is the simulation time, which increases as detailed models are used in both pre-crash and crash-phase, but this can be addressed to some extent by dynamic model simplifications, such as switching deformable to rigid materials [15].

Seamless whole-sequence simulations have been utilized to study braking followed by frontal impact in vehicle environments [13-19], but not yet for other types of impact and pre-crash manoeuvre. Initial work has been conducted for side impacts with occupant on the non-struck side (Far-Side), using an Active HBM in a simplified experimental seat [16]. The study included pre-crash braking in combination with a side-impact crash pulse and six muscle activations strategies for the crash phase. Recommendations from the study included to keep muscle activations constant from the start of the impact, or to turn muscle activation off, which would be in accordance with the sequential method described above [10], for which muscle activation was not reinitialized. Furthermore, Far-Side impact is a relatively long duration crash event, which was targeted in a study with an early Active MultiBody HBM [1]. For this reason, an active spine and extremity model was used with the Madymo HBM [1] and the authors concluded that the active responses gave a significantly different response than with the passive model in this crash configuration.

The overall purpose of the current study was to study seamless whole-sequence simulations in Far-Side impacts preceded by braking, using an Active FE HBM in vehicle environment. The study explored occupant responses when exposed to variations of side-impact point and impact speed, in combination with one pre-crash and one in-crash activated restraint.

II. METHODS

Whole-sequence FE simulations were created by running a pre-crash braking intervention followed by a barrier side-impact pulse from a passenger-side impact to a complete vehicle model. Simulations were performed with the explicit FE solver LS-DYNA MPP R9.3.1 (ANSYS/LST, Livermore, CA). The occupant model used was the Active SAFER HBM version 10 [20-21], positioned in the driver seat of a passenger car compartment model. FE restraint models were used, consisting of a seatbelt with a reversible pretensioner, a function commonly called electrical reversible retraction (ERR), and in-crash pretensioner, as well as a simplified simulated functionality of two far-side airbags (FSABs), Fig. 1.

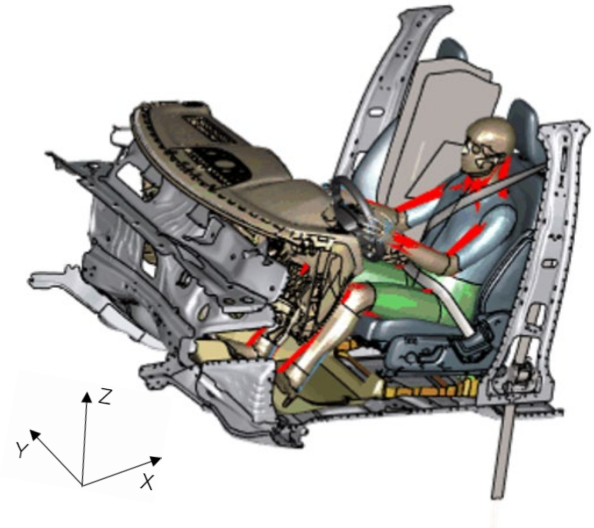

Fig. 1. The SAFER HBM in the passenger car compartment model used, together with the initial geometry of the simulated unfolded FSABs before inflation.

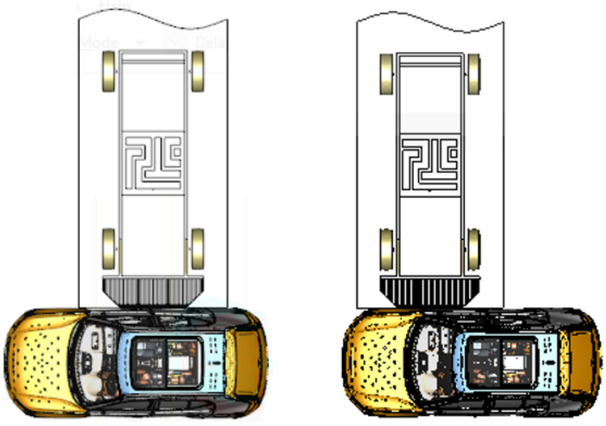

Fig. 2. Setup of the complete vehicle simulation side-impact configurations: mid-compartment (left) and one meter forward of mid-compartment (right).

The SAFER HBM has the ability to predict sitting occupant postural responses when subjected to a pre-crash braking or steering scenario, using an angular position feedback control system to generate a muscle activation response that is proportional to the displacement of the model due to external loading [20]. The control objective for the feedback control is to maintain the initial position of the model in the simulation. Furthermore, the biofidelity of the SAFER HBM in the Far-Side impact has been validated against post-mortem human subjects' (PMHS) data, using kinematic corridors and correlation analysis [21] for the passive HBM. For this study, the active muscle control [20] was extrapolated also to the crash-phase.

Impact positions and speeds

Complete vehicle simulations with the AE-MDB (ANSYS/LST, Livermore, CA) barrier impacting the side of the standstill vehicle were used to record crash pulses as input to the passenger car compartment model. One run with barrier impact speed in 60 km/h and one in 70 km/h were made for both impact configurations (Fig. 2). The mid-compartment impact configuration was set up by aiming the mid-line of the barrier towards a point 250 mm rearward of the H-point of an SAE manikin, in the seat positioned to mid fore-aft travel (in accordance with [22]). The other impact position was 1 m in front of the impact position of the mid-compartment impact configuration (Fig. 2).

The complete vehicle simulations were run for 200 ms to ensure that the pulse was long enough to capture the maximum lateral head excursion and a potential head impact. Recorded pulses were 6 Degrees-of-Freedom (6DOF), meaning that they include both translations and rotations, see Figure 10 in the Appendix.

Simulation matrix

In total, 10 simulations were run, including variations of the impact configuration (mid-compartment impact and 1 m forward) and barrier impact speeds (60 km/h and 70 km/h), with and without activation of ERR and FSAB functionality, see Table I. Simulations No. 1 and 4 were run as baselines for comparison. In No. 1, no pre-crash phase was included. No. 4 was the only one without activation of the FSABs. Both were run in 60 km/h in the mid-compartment impact configuration.

TABLE I
SIMULATION MATRIX

Simulation No.	Pre-crash phase	FSABs	ERR 250 N	Impact speed (km/h)	Impact configuration
1	No	Yes	No	60	Mid*
2	Yes	Yes	Yes	60	Mid*
3	Yes	Yes	No	60	Mid*
4	Yes	No	No	60	Mid*
5	Yes	Yes	Yes	60	Front**
6	Yes	Yes	No	60	Front**
7	Yes	Yes	Yes	70	Mid*
8	Yes	Yes	No	70	Mid*
9	Yes	Yes	Yes	70	Front**
10	yes	Yes	No	70	Front**

**Mid: mid-compartment impact configuration.*

***Front: impact position 1 m forward of the mid-compartment impact configuration.*

Pre-crash and crash event

The whole-sequence simulations can be explained as three events in one simulation. First, 300 ms of HBM initialization and settling, followed by 500 ms pre-crash braking and, lastly, 200 ms crash phase (Fig. 3). The HBM settling had the purpose of obtaining equilibrium between the seat and the HBM, initializing the muscle control system and maintaining an upright posture using the feedback control. After the initialization, the pre-crash phase began, with a braking acceleration of 1 g that was smoothly ramped up during 200 ms and held for 300 ms. At the start of the pre-crash phase the ERR function was applied. Lastly, after 800 ms of simulation, the crash phase began (time of impact). This triggered several changes in the model. Rigid parts were switched into deformable, the Active HBM's arms and legs were switched into passive mode, FSABs and in-crash seatbelt pretensioners were deployed after 5 ms.

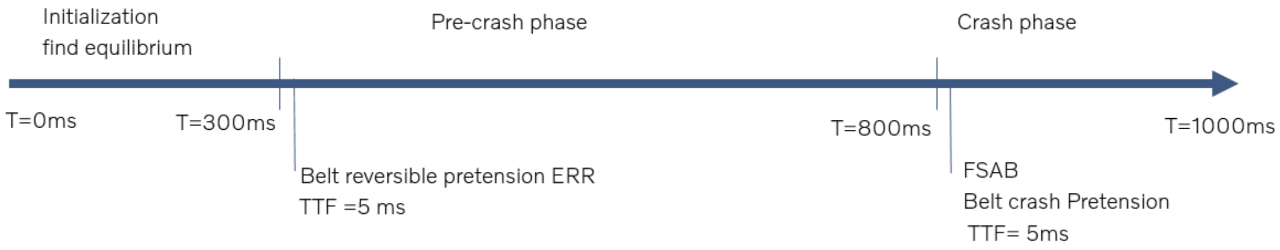

Fig. 3. Timeline for the whole-sequence crash simulations.

Restraint system models

The FSAB functionality was modelled with unfolded airbags that were attached on the side of the seat frame of the driver and the front passenger seat, respectively (Fig. 4). They were activated in all the simulations, except in the baseline simulation No. 4. The FSAB CAE model was made of two fabric pieces stitched together around the edges, with four separated tubular cells in the middle part of the airbag. On the top and bottom there were larger volumes (Fig. 4). The two FSABs were always deployed together and 5 ms after the crash phase was initiated. They reached a working pressure of 50 kPa 40 ms after deployment. This was modelled with the *AIRBAG_LOAD_CURVE keyword that use a pre-defined pressure vs. time curve.

The seatbelt retractor model had two settings used in the pre-crash phase. First, the ability to simulate an ERR function with 250 N of tension force, referred to as "yes" with respect to ERR in Table I. The other setting was to lock the retractor from paying out seatbelt webbing and applying a lower passive tension force of 20 N to the seatbelt, referred to as "no" in Table I. In-crash pretension was simulated in the crash phase with a Time To Fire (TTF) 5 ms after start of crash phase included for all simulations. This functionality is commonly implemented with pyrotechnics (irreversible pretension).

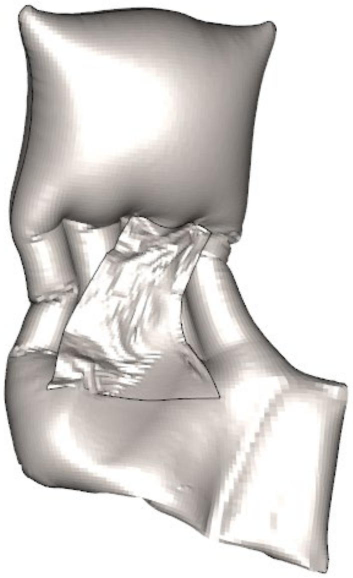

Fig. 4. FE model of the FSAB function with a shoulder-level wrap-around strap and a larger head and torso part.

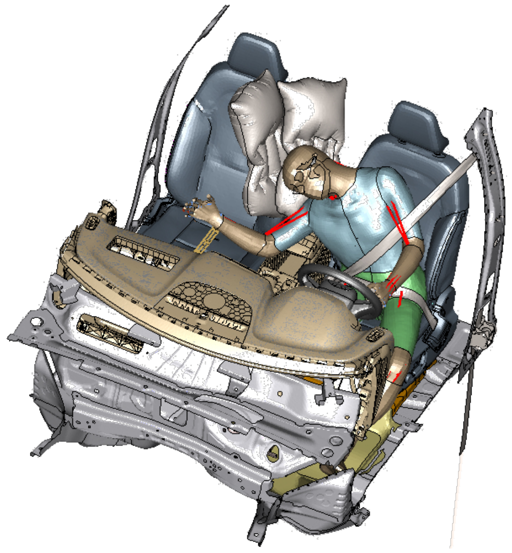

Fig. 5. The simplified car compartment model used for the parameter study, showing the dual FSABs activated in the crash phase of simulation No. 3.

Car compartment model

The model was built on a rigidified body-in-white that was controlled in both translation and rotation. Mounted on the rigid body were deformable interior parts, representing front seats, tunnel console, instrument panel, pedals, seat belt and the two FSABs (Fig. 5). Until the crash phase, most of the parts were kept rigid. To ensure numerical stability and reproducibility, only the driver seat and HBM were kept deformable during the pre-crash phase. Intrusions or relative motions recorded from the complete vehicle simulations were not included in the car compartment model, since they were small and did not cause any direct interactions with the HBM or the restraint systems.

Analysis

Displacements and SAFER HBM tissue level injury predictions were analysed and presented in a vehicle fixed coordinate system with X rearward in the longitudinal direction, Z upward in the vertical direction, and Y to the left, Fig. 1. The maximum lateral head excursion was analysed relative to the two baseline simulations and visualized for easy comparison to three vertical planes, representing the near-side seat centreline, 125 mm and 250 mm inboards, respectively, similar to the Euro NCAP rating procedure [22].

III. RESULTS

All 10 simulations were numerically successful and reached the full simulation time, i.e. normal termination.

The pre-crash phase

The settling and pre-crash phase resulted in a position of the HBM at time of impact, which was in front of and below the initial position: 92 mm, 52 mm and 20 mm in the forward or negative X direction, and 45 mm, 30 mm and 8 mm in the vertical or negative Z direction for the head, sternum and pelvis, respectively.

The position at time of impact was influenced by the modelled ERR activation (Fig. 6). With activation of the ERR in the pre-crash phase, the HBM obtained a position at time of impact that was more rearwards and down, compared to no ERR function. A difference of 22 mm, 27 mm and 10 mm in the forward direction and 15 mm, 9 mm and 4 mm down in the vertical direction was observed for the head, sternum and pelvis, respectively. Hence, the ERR held the HBM more towards the seatback, while also pulling it slightly down. The reason that the head had less forward excursion than the sternum was because of the active muscles of the HBM trying to maintain the initial position when the muscle controllers were active.

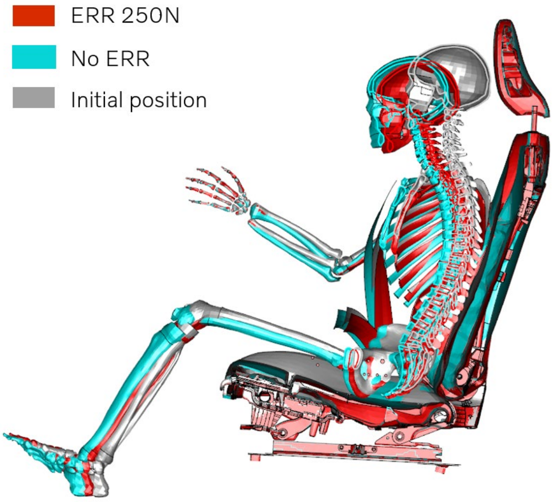

Fig. 6. Comparison of HBM positions at time of impact (800 ms) with respect to ERR function activation. The grey HBM shows the initial position at the start of the pre-crash phase (300 ms). The red HBM shows position at time of impact for the simulations with activated ERR function (simulations No. 2, 5, 7 and 9) and the turquoise HBM those without (simulations No. 3, 4, 6, 8 and 10).

Influence of impact configuration and impact speed

The higher impact speed of 70 km/h, as compared to 60 km/h, resulted in higher maximum Y lateral head excursion up to 70 mm, Table II. This is shown in Fig. 7, pairwise comparing the two impact configurations, respectively. The higher speed also influenced the vertical position of the head at the time of maximum lateral head excursion.

Compared to the mid-compartment impact configuration, the 1 m more forward impact configuration caused a lower lateral pulse and more rotation of the vehicle about the vertical axis. For the simulations without ERR activation, this resulted in 50 mm less peak lateral head excursion and 60 mm more total forward head excursion for the HBM in the 60 km/h impact speed (Fig. 7). A similar pattern was seen in 70 km/h, with about 40 mm lateral head excursion reduction. When comparing the simulations with ERR activations, the same trends were seen, but with less lateral excursion (Fig. 7).

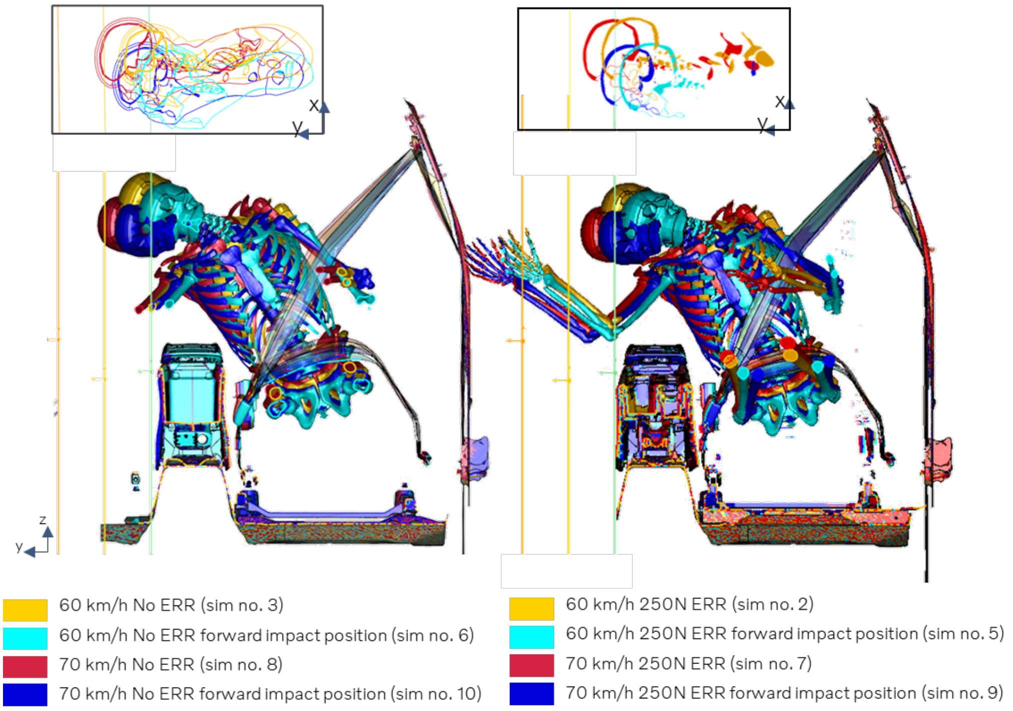

Fig. 7. Comparison of maximum head lateral excursion with respect to impact configuration and impact speed, without ERR function (left) and with ERR function (right). All runs included the FSAB functionality, and the snapshots are taken at 932 ms (max. head lateral excursion).

TABLE III

PEAK HEAD CENTRE OF GRAVITY DISPLACEMENTS IN MM. X AND Z DISPLACEMENTS REPORTED AT THE TIME OF PEAK Y DISPLACEMENT.

Simulation No.	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Head X displacement at peak Y displacement	0	-10	-30	20	-70	-90	-30	-20	-50	-70
Head peak Y displacement	470	430	470	510	380	420	480	530	450	490
Head Z displacement at peak Y displacement	-130	-140	-120	-180	-130	-140	-150	-160	-150	-150

Influence of ERR and FSAB functionalities

For all included impact configurations and speeds, activation of the ERR function resulted in less head lateral excursion by 40–50 mm in the crash phase, compared to no activation. ERR activation caused a more restrained pelvis compared to not activating the ERR, which was observed in the pelvis roll angle and vertical excursion at the time of maximum head excursion (Fig. 8). Activating the FSAB functionality shortened maximum head lateral excursion by 40 mm in the 60 km/h mid-compartment impact configuration. More lateral pelvis movement was observed when no FSAB functionality was included, comparing two runs with and without (simulations No. 3 and 4). Activating both the FSAB and ERR functionalities resulted in 80 mm less head lateral excursion, compared to no activation (simulations No. 2 and 4).

There was some difference in whole body kinematics between the simulation without the pre-crash (No. 1) and a whole-sequence simulation (without ERR, No. 3), but only a minor difference in peak head lateral excursions, Fig. 8.

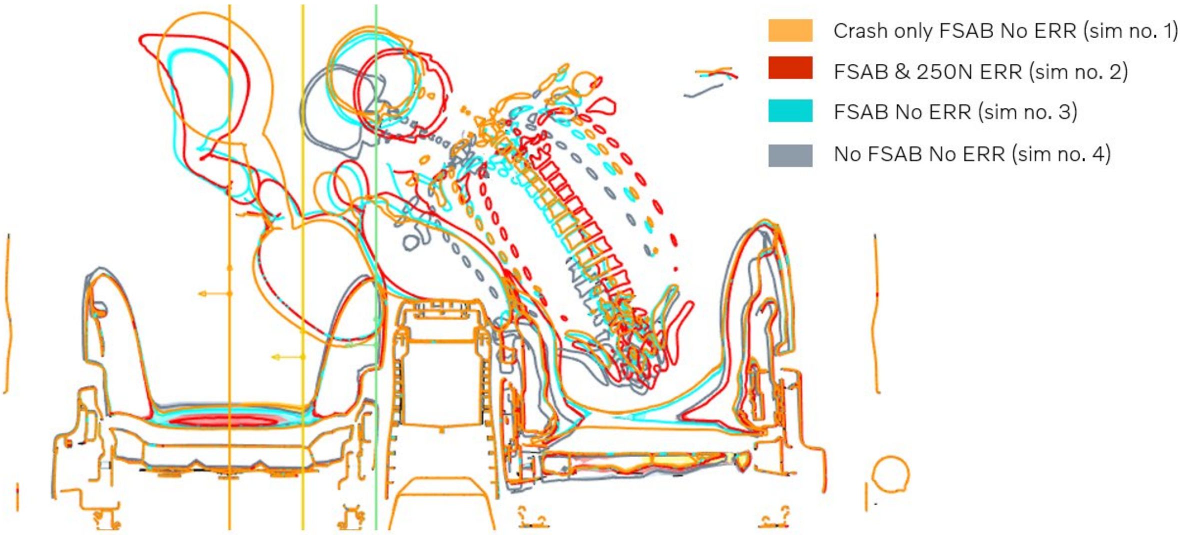

Fig. 8. Comparison of maximum head lateral excursion with respect to influence of FSAB and ERR functionalities in mid-compartment impact configuration and impact speed 60 km/h. Snapshots are taken at 932 ms (max. head lateral excursion).

Injury prediction

SAFER HBM injury predictions indicated low risk of injury in all simulations, with peak brain Maximum Principal Strain (MPS) below 0.18 corresponding to 22% of AIS1+ concussion [23], and a combined probabilistic rib fracture risk of close to 0% for two or more rib fractures [24]. The ribs with highest rib strains were ribs 8–10 (Fig. 9), with rib strains of up to 1.0% indicating a low risk of injury [24]. The highest peak rib strain was found in the 60 km/h simulation without FSAB functionality (Simulation No. 4). Spine force and bending moments measured with cross-sections showed a peak lower neck tensile load of 1.3 kN, well below injury reference assessment values of 3.1 kN [25], and moderate lower neck bending moments. The cases with highest neck loads were simulations with mid-compartment impact configuration and without FSAB functionality, or in 70 km/h without ERR function and with FSAB functionality.

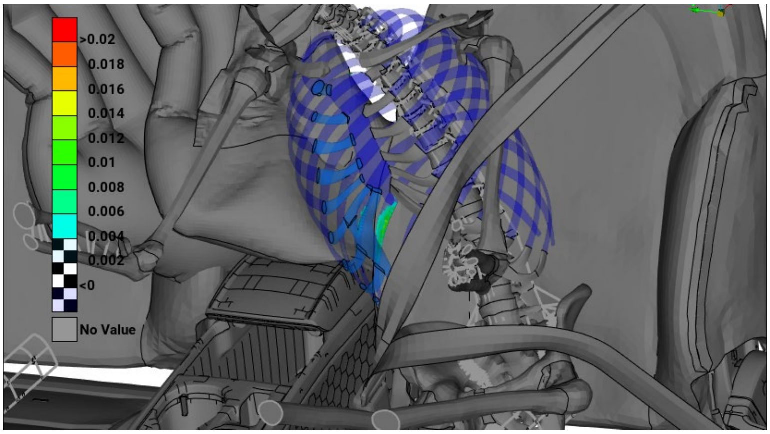

Fig. 9. Fringe plot of first principal strain at the ribs in a 70 km/h mid-compartment impact without ERR and with FSABs at 892 ms (simulation No. 8).

IV. DISCUSSION

The SAFER HBM was successfully applied in the driver position in a series of seamless whole-sequence simulations that combined a pre-crash braking intervention followed by a Far-Side impact. This combination has not been studied before in a vehicle environment and demonstrates an important step in occupant protection evaluations representing real-world-type situations. Starting in 2016 with the first seamless whole-sequence simulations of longitudinal events of braking followed by frontal impacts [13-14], several model advances have taken place to enable this step. Of particular importance was the incorporation of omni-directional postural control [20, 26], which allows the model to also respond to lateral and combined pre-crash manoeuvres. In the current study, the SAFER HBM model proved to function robustly in the simulations considering the complexity in the combination of the low-g and high-g events, the challenging side-impact kinematics, including different degree of vehicle rotation and variations in restraint interactions. All simulations were executed with normal termination.

Real-world crashes are diverse and complex as compared to standardized tests, which are executed without any pre-crash intervention. With increased degree of vehicle driving automation, the number of real-world crashes with preceding braking and steering may increase [27]. This study shows that pre-crash braking may influence the occupant position at impact, as well as may be influenced by pre-crash activated restraints, here exemplified by an ERR function. To further guide the development of pre-crash and in-crash restraints requires occupant tools with seamless whole-sequence capability, and this is an important purpose for Active HBMs.

The study investigated the possible influence of pre-crash braking and the influence of impact configuration and impact speed, in addition to restraint interventions for a driver when exposed to a Far-Side impact. It was seen that pre-crash brake intervention positioned the occupant in a more forward position at time of impact, although to a less extent when ERR functionality was activated. Volunteers exposed to a braking event show similar occupant response [8-9]. The brake intervention also influenced the vertical position of the HBM model. When comparing the simulation without braking to the corresponding with braking, it was seen that the maximum head lateral excursions during the Far-Side impact were relatively similar. Although not completely comparable from a real-world crash perspective (entering the event at different speeds), it shows that the pre-crash braking alone did not largely influence the in-crash head lateral excursion, despite there being a difference in the initial crash position. However, there was an influence on the head lateral excursion when adding interventions, both in the pre-crash and in-crash phases. This shows the usefulness of seamless pre-crash to crash phase simulations, since the in-crash results are dependent on the force balance and occupant position built up during pre-crash phase. Here, the ERR functionality applied in the pre-crash phase reduced seatbelt slack and further supported occupant coupling to the vehicle before crash.

The models of the FSAB functionality were activated in all except one of the simulations. In comparison to the baseline simulation without activation, it was seen that the pelvis lateral movement and pelvis side rotation were less with FSAB functionality, also resulting in a 40 mm reduced head lateral excursion. This shows that restraining the pelvis can influence the magnitude of head lateral excursion. Similarly, activation of the ERR function reduced the slack in the seatbelt and restrained the occupant more towards the seat.

When altering impact point on the vehicle, it was seen that the differences in vehicle rotation and lateral crash pulse influenced occupant kinematics during crash. A more forward impact point shifted the head excursion more forwards, reducing the lateral and increasing the longitudinal component.

This study is one of the first implementations of combined whole-sequence simulations for a Far-Side impact, and as such the study contains a number of limitations that should be highlighted. For instance, while the simulation methodology showed the capability of the HBM for seamless simulations, further refinement of the whole-sequence scenario to become more real-world like is possible. It is probable that a pre-crash steering manoeuvre would lead to an initial more inboard position that could be of importance. Furthermore, the whole-sequence simulation here was created by the extension of a laboratory side-impact test method, using a barrier model and a stationary struck vehicle. Using two vehicle models, with initial velocities of both the bullet and struck vehicle could change the struck vehicle kinematics and remains to be investigated. Lastly, the HBM kinematic response to Far-side impact has been validated for the passive HBM with respect to human subject data [21] and the postural control response to lateral pre-crash motions [20] but using the muscle controller during the Far-Side crash phase is an extrapolation of the current HBM's capabilities.

V. CONCLUSIONS

The SAFER HBM positioned in the driver seat was shown capable of seamless whole-sequence simulations combining a pre-crash braking intervention followed by a side impact to the passenger side (Far-Side impact). This opens the way for a larger range of real-world representative combinations of occupant protection evaluation, and to include in-crash as well as pre-crash activated restraints as protection means. The study showed that airbag functionality (activated in the in-crash phase) as well as an ERR functionality (activated in the pre-crash phase) have potential to contribute to help reduce head lateral excursion. In addition, when altering impact point on the side of the vehicle, it was seen that the differences in vehicle rotation influenced occupant kinematics during crash.

VI. ACKNOWLEDGEMENTS

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VIII. APPENDIX

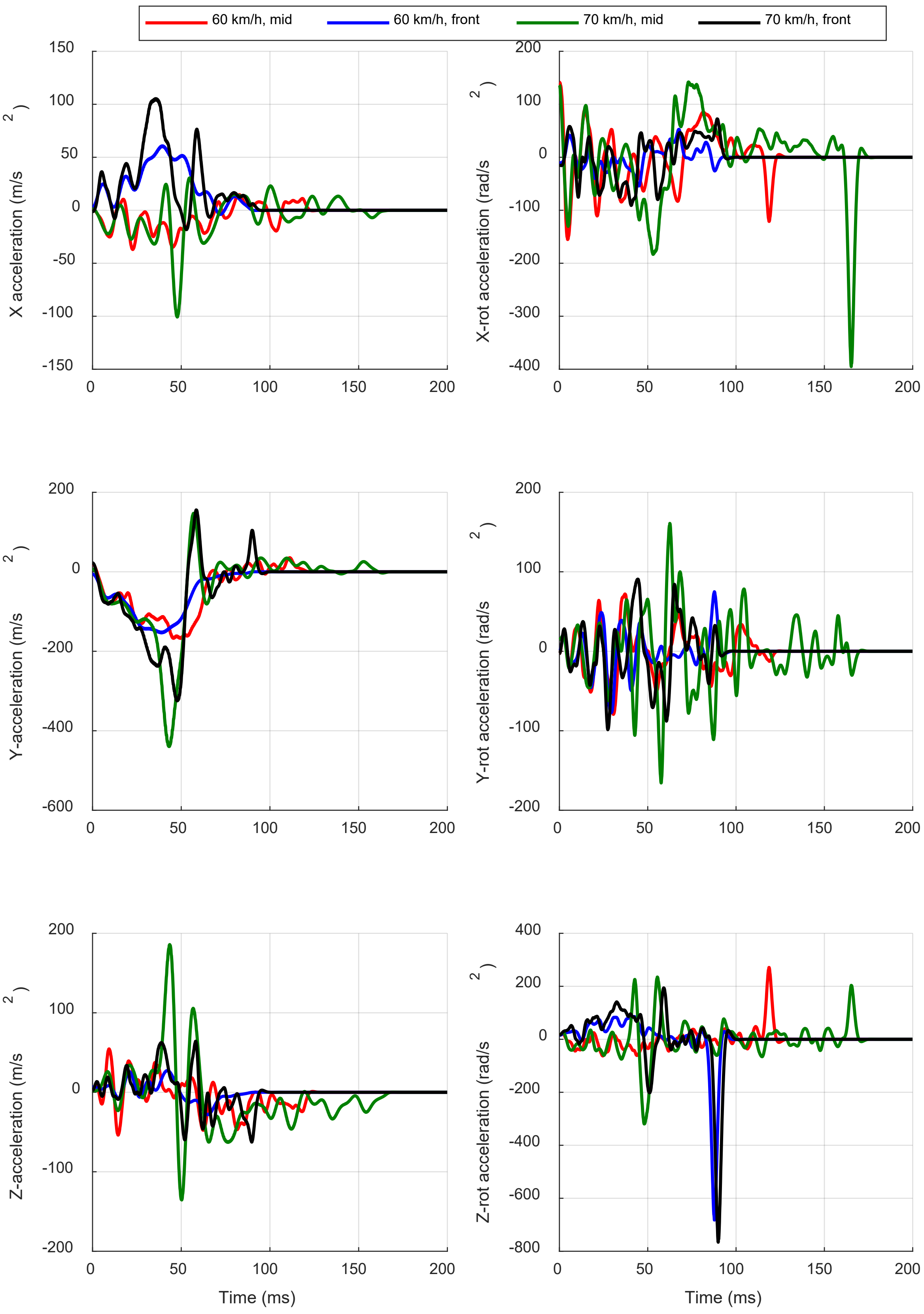

Fig. 10. Six degrees of freedom accelerations in the global coordinate system, Fig.1, for the passenger car compartment model in the four simulated side impact configurations.