An Examination of Pre-crash Braking Influence on Occupant Crash Response using an Active Human Body Model

Merete Östmann, Lotta Jakobsson

Abstract Real-world occupant protection includes the influence of active safety technologies, such as auto-brake systems. This study uses an active human body model (called SAFER A-HBM) with the capability to simulate emergency braking events prior to a crash event. It is based on a mid-sized male THUMS human body model, with added active muscles to control spine and extremities for braking.

The objective of this study is to evaluate the feasibility of the A-HBM for industrial applications in the development of occupant protection technologies. Specifically, the influence on occupant responses in frontal impacts with a preceding braking event is simulated, including variation in brake-pulse duration and activation of an electrical reversible seatbelt retractor.

All the simulations followed through to the most important part of the crash phase, enabling a comparison of the occupant responses for the different simulation set-ups. By adapting its characteristics depending on the sequence of the event, the A-HBM is shown to be a feasible tool providing input to help guide the auto-brake performance design. Using it to replicate human performance during the whole sequence of pre-crash to crash event enables a real-world, realistic comparison that provides unique possibilities to evaluate active and passive safety technologies together and their interaction.

Keywords Active Human Body Model, auto-brake, occupant protection, FE-model, LS-Dyna.

I. INTRODUCTION

Human Body Models (HBMs) are valuable tools to simulate the pre-crash and in-crash occupant response in order to develop advanced restraint systems and reconstructions of real-world crashes. In addition, as compared to crash test dummies, the HBMs have improved anthropometry and thereby offer possibilities to provide insight into probable injury mechanisms and to help determine injury criteria. These injury criteria are essential in assessment methods of new restraint systems. As compared to physical crash test dummies, HBMs can have biofidelic sensitivity to different loading directions (omnidirectional design) and differences in acceleration levels. HBMs can represent different occupant sizes, gender, anthropometry and muscle tonus, and are predicted to be essential tools for future virtual testing and verification.

Today, real-world occupant protection is more than simply conventional passive safety technologies, exemplified by car body structure design, seatbelts and airbags. During the last decade, a rapid development of auto-brake technologies has taken place. While quite exotic 10 years ago, today most vehicle manufacturers offer some form of collision avoidance systems on their vehicles, at least as an option package [1]. In 2006, brake support was introduced by Volvo Cars [2], followed by a second generation, called *Collision warning with Auto Brake,* which could provide automatic emergency braking up to 5 m/s^2 in certain lead vehicle conflict situations [3]. In 2008 the first auto-brake system enabling crash avoidance at low speeds, was introduced, and has now reached a relatively large market penetration [4]. Some years later, the systems could achieve automatic emergency braking up to 10 m/s^2, and not just for cars but for certain pedestrian conflicts as well [5]. In 2013, the world's first *Cyclist Detection and Auto Brake* system expanded the list of objects the car could autonomously brake for, and in 2015 the system added more cyclist and vehicle interaction situations that the car can act on, such as when turning in front of an oncoming vehicle at intersections [1]. The developments of

M. Östmann (e-mail: Merete.ostmann@volvocars.com; tel: +46 31 3252066) is Senior CAE engineer and L. Jakobsson is Senior Technical Leader at Volvo Cars Safety Centre. L. Jakobsson is also Adjunct Professor in Vehicle Safety at Chalmers University of Technology Centre and reference group leader at SAFER, Vehicle and Traffic Safety Research Centre at Chalmers, Göteborg, Sweden.

active safety technologies are important to address from an occupant protection perspective, since they may help to protect the occupants by mitigating the crash severity, if not avoiding the crash as such. In the development of such technology it is also essential to provide input from occupant protection performance to enable optimal setting of the technology and the interactive performance with occupant restraints and other passive safety technologies.

Human body models will play an important role in future safety developments of vehicles. From a real-world safety development perspective, there is a considerable need for active HBMs. Manoeuvres prior to an impact are a reality and therefore are necessary to simulate in order to develop occupant protection systems for these situations. Important features for such tools are predictivity and degree of detail adaptable for in-vehicle simulation. A number of active HBM exists today, using different modelling techniques, as summarized in [8]. Simulating driver and passenger kinematics in pre-crash and emergency events, using muscle activity regulated by closed loop control, at least one finite element (FE) [6] and one multi-body [7] whole-body occupant HBM have been presented. Using closed loop control enables predictivity. In comparison, the finite-element model [6] has the ability to predict injuries in more detail than multi-body HBM and is more adaptable for in-vehicle simulation, while the multi-body HBM has the main strength for kinematics simulation. Both of these models are of average male anthropometry. They have been evaluated with respect to volunteer data in longitudinal loading situations. Further developments are needed, and are ongoing, with respect to occupant characteristics as well as different directions of loadings [8].

Using an active HBM provides unique possibilities to evaluate active and passive safety technologies together and their interaction. In the absence of such a tool, a combination of volunteers and crash test dummies have been used to evaluate the effect of pre-braking on occupant response [9-10]. The SAFER A-HBM is the first of its kind to simulate a braking event with a subsequent crash, adapting its characteristics depending on the sequence of the event [8]. The overall objective of this study is to evaluate the feasibility of the SAFER A-HBM for industrial applications in development of occupant protection technologies. Specifically, as a first step, the influence on occupant responses in frontal impacts with a preceding braking event is studied and parameters such as brake-pulse duration and activation of an electrical reversible seatbelt retractor are varied.

II. METHODS

An active human body model, called SAFER A-HBM, with the capability to simulate emergency braking events with a subsequent frontal impact was used [8]. The model is based on a 50th percentile male-sized THUMS HBM, with added active muscles to control spine and upper and lower extremities for braking, and it is run in LS-Dyna (Fig. 1(a)). The model's braking capability is validated using volunteer tests [11-12]. The SAFER A-HBM is placed in a complete vehicle interior model of a Volvo S60 (year model 2010) (Fig. 1(b)). One initial sitting posture and seatbelt routing is used throughout the simulation series. A seatbelt with and without electrical reversible retractor (ERR), activated at 200 ms with a force of 300 N, is included in two simulations. Seatbelt slack is not added in this simulation series. In the crash phase a pyrotechnical belt pretensioner, an airbag initially placed in the steering wheel and a collapsible steering column are also present.

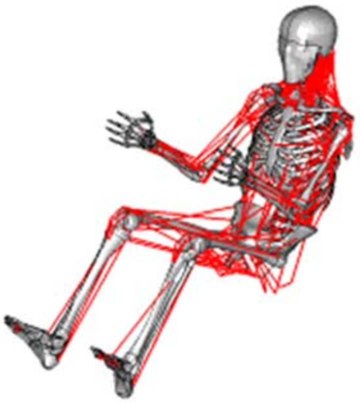

Fig. 1(a). SAFER A-HBM, skeleton and muscles.

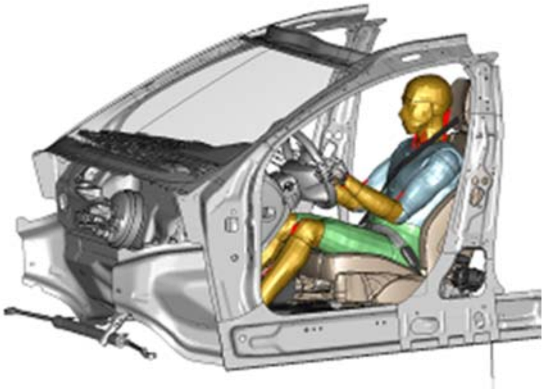

Fig. 1(b). Complete A-HBM and vehicle interior model.

The frontal impact represents complete vehicle tests at 0 degree angle and 40% overlap using the EuroNCAP deformable barrier of varying speed: 64 km/h down to approximately 56 km/h and 39 km/h, respectively. The acceleration level of the crash pulse at 64 km/h reaches approximately 35g. The variation of impact speed is set depending on the brake effect on the speed reduction. The brake pulse is set to 1 g which is reached 350 ms after brake trig. Two different brake durations are used to enable the desired speed reduction. Details on the six simulations are shown in Table I. The whole simulation sequence is illustrated in Fig. 2. The total duration is up to 1650 ms, including a model stabilisation phase, a long brake phase of varied length, and a crash phase of up to 200 ms.

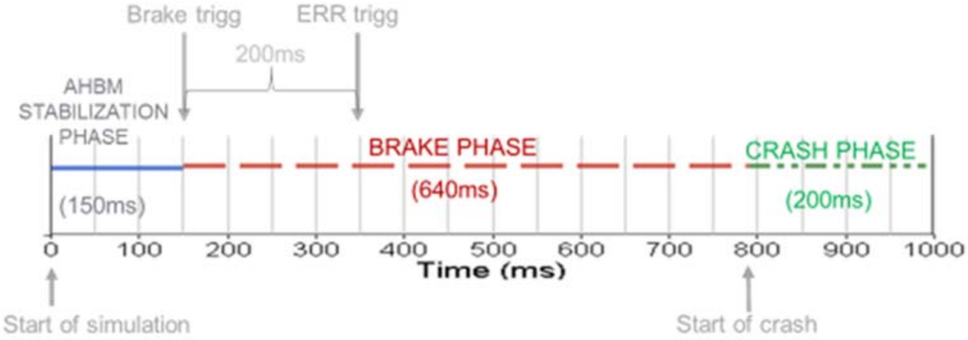

Fig. 2. Simulation sequence, approximate timings. Brake phase duration was varied in this study.

TABLE I
SIMULATION SET-UP MATRIX

Run nr	Starting speed (km/h)	Impact speed (km/h)	Brake duration (ms)	Electrical reversible retractor
1	64	64	0	No
2	56.5	56.5	0	No
3	64	56.5	640	No
4	64	56.5	640	Yes
5	64	39.2	1320	No
6	64	39.2	1320	Yes

The analyses include comparing occupant restraint interaction throughout the whole sequence kinematically, as well as comparison of some occupant responses. The occupant responses selected in this study are resultant accelerations at head centre of gravity, thoracic spine vertebra T4 and pelvis, together with chest deflection. Chest deflection (ribs relative to spine) is measured at several points, including the four locations comparable to the positions of a THOR crash test dummy. The chest deflection measurement point with highest response (upper right position) is selected for inclusion in the paper.

III. RESULTS

All the simulations followed through to the most important part of the crash phase, enabling a comparison of the occupant responses for the different simulation set-ups. Simulations nr 4 and 6 terminated just prior to reaching maximum forward excursion.

Influence of speed reduction by pre-braking

Comparing runs 1, 3 and 5, the influence of speed reduction in pre-braking is seen. The simulation set-ups, including seatbelt characteristics, are identical. Run 1 simulates a crash at 64 km/h without any pre-braking phase, while runs 3 and 5 include a pre-braking phase, simulating an auto-brake system reducing the impact speed to 56.5 km/h and 39.2 km/h, respectively. The effect of occupant kinematics and seatbelt interaction during the pre-brake phase can be seen in runs 3 and 5, resulting in a difference in the occupant's sitting posture at time of impact as compared to no pre-braking (Fig. 3(b)). This together with the difference in impact severity influences the crash phase, which can be seen in Fig. 3(c), showing the most forward occupant position during the crash phase. The occupant responses during the crash phase are presented in Fig. 4. The influence of speed reduction by pre-braking is clearly shown by reductions in the acceleration values of 15–45% and 60–70%, by pre-braking from 64 km/h to 56.5 km/h and 39.2 km/h, respectively. The maximum chest deflection response, as measured in this study, did not show any obvious difference (Fig. 4).

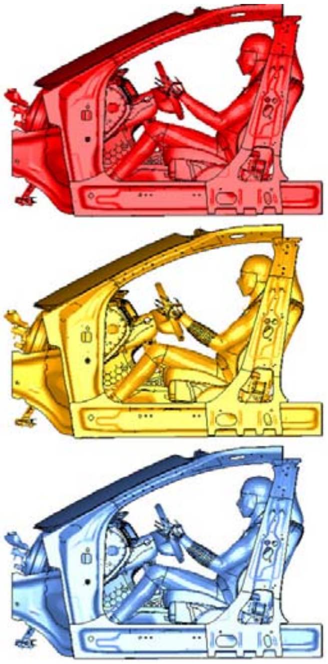

Fig. 3(a). Initial sitting posture; runs 1 (no pre-brake), 3 (pre-brake to 56.5 km/h) and 5 (pre-brake to 39.2 km/h) from top to bottom.

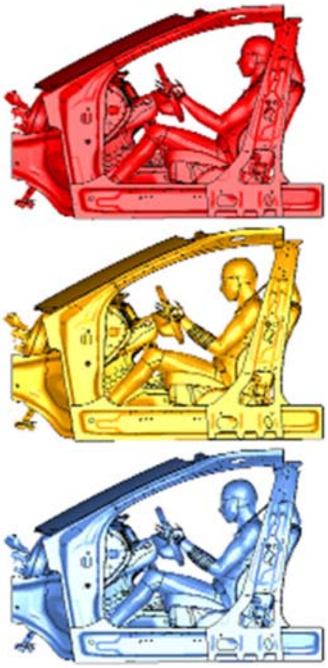

Fig. 3(b). Posture at time of impact (start crash pulse); runs 1 (no pre-brake), 3 (pre-brake to 56.5 km/h) and 5 (pre-brake to 39.2 km/h) from top to bottom.

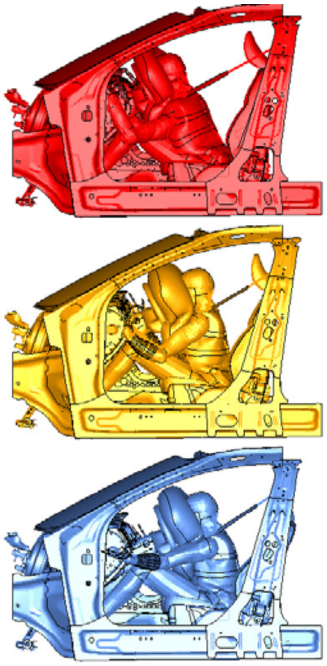

Fig. 3(c). Posture at most forward occupant position; runs 1 (no pre-brake), 3 (pre-brake to 56.5 km/h) and 5 (pre-brake to 39.2 km/h) from top to bottom.

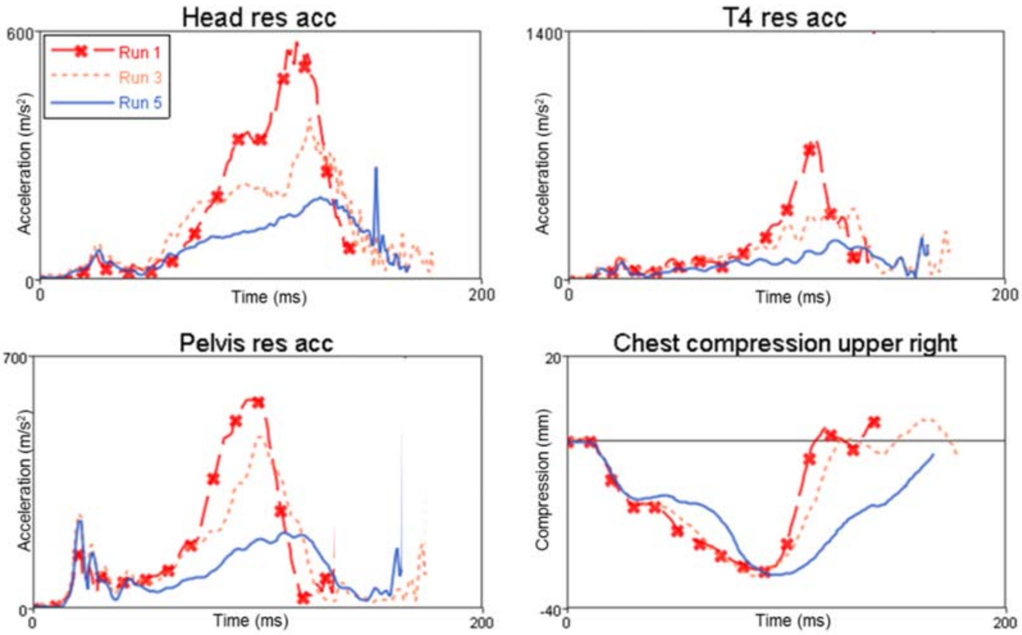

Fig. 4. Occupant responses comparing influence of speed reduction by pre-braking to 56.5 km/h (run 3) and 39.2 km/h (run 5) to frontal impact at 64 km/h without pre-braking (run 1).

Influence of pre-braking on occupant kinematics and responses

Simulations 2 and 3 are compared to provide insight into the differences of occupant posture as a result of a pre-brake situation as compared to no pre-braking. The occupant in run 3 was subjected to a pre-braking from 64 km/h. The occupant in run 2 was stationary until exposed to the same frontal impact crash pulse as in run 3, hence the only difference in this comparison is the occupant position at impact, as seen in Fig. 5(b). This resulted in some slight differences in the kinematic responses (Fig. 5(c)) and occupant responses (Fig. 6). The main difference could be seen in head acceleration characteristics.

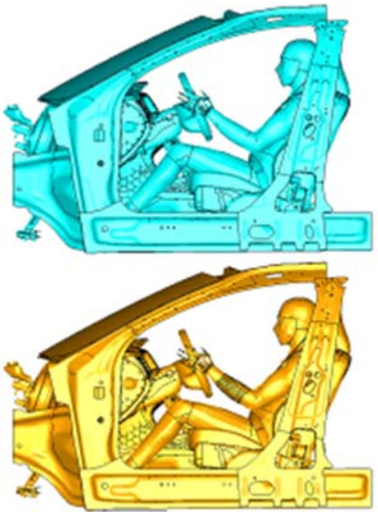

Fig. 5(a). Initial sitting posture; runs 2 (pre-brake, *top*) and 3 (no pre-brake, *bottom*).

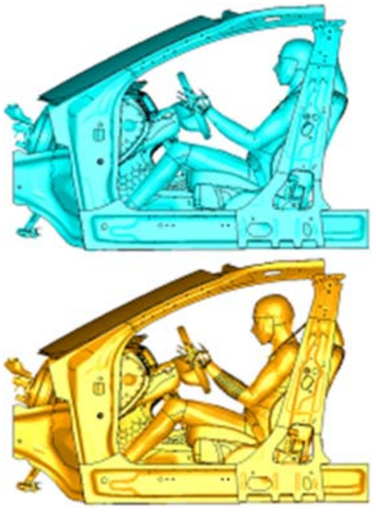

Fig. 5(b). Posture at time of impact (start crash pulse); runs 2 (pre-brake, *top*) and 3 (no pre-brake, *bottom*).

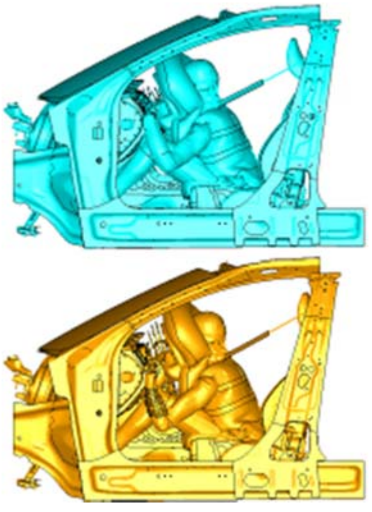

Fig. 5(c). Posture at most forward occupant position; runs 2 (pre-brake, *top*) and 3 (no pre-brake, *bottom*).

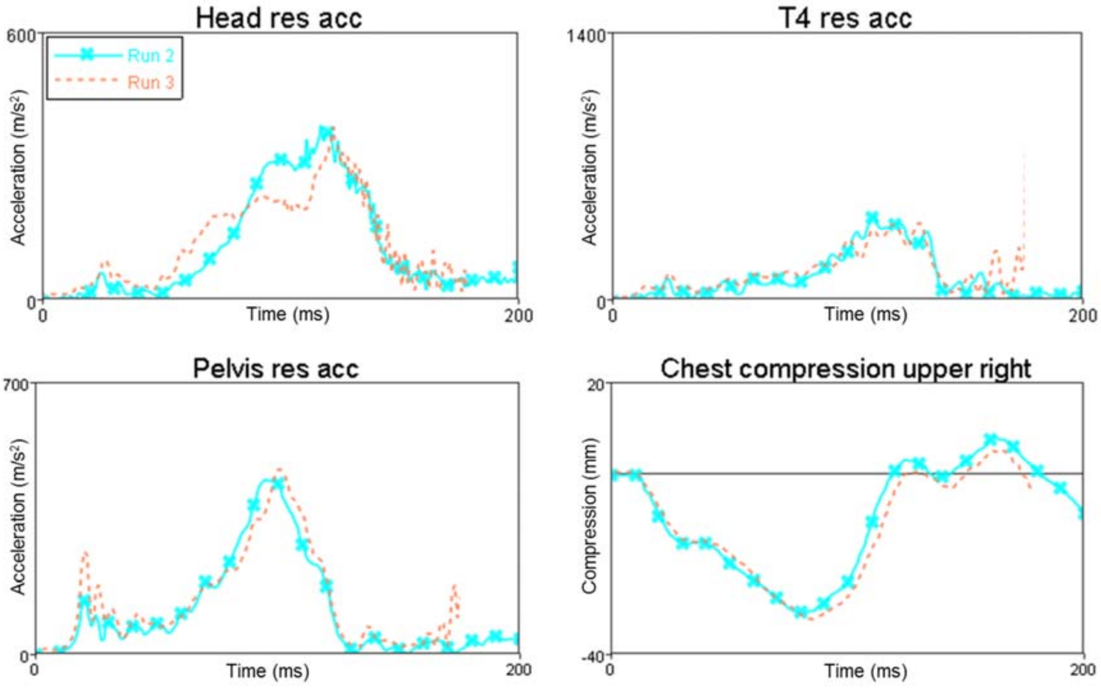

Fig. 4. Occupant responses comparing influence of pre-braking (run 2) to frontal impact with same speed without pre-braking (run 3).

Influence of activation of electrical reversible retractor

Two of the simulations, runs 4 and 6, were repeated and an electrical reversible retractor (ERR) was added. Both of these had numerical instability and only reached 138 ms and 126 ms, respectively, of the 200 ms crash event. These simulations are pairwise compared to their counterparts without ERR, i.e. runs 3 and 5, respectively. The two sets of simulations are exposed to pre-brake of different duration, resulting in impact speed of 56 km/h and 39.2 km/h, respectively.

Although difficult to see in Figs 7(b) and 8(b), the torso is kept back by the ERR during the pre-brake phase, resulting in approximately 3 cm less forward head position in the ERR runs as compared to the runs without ERR. Unfortunately, neither of the ERR runs reached the maximum forward excursion and are therefore excluded in Figs 7(c) and 8(c).

Comparing the occupant responses, there is no major difference within the pairwise comparisons (Fig. 9). Hence, in this simulation series, the effect of ERR on occupant response is not obvious. The situations simulated in this study represent upright sitting posture and perfect seatbelt conditions (without slack), for which the ERR helps only to limited extent to position or retract the occupant.

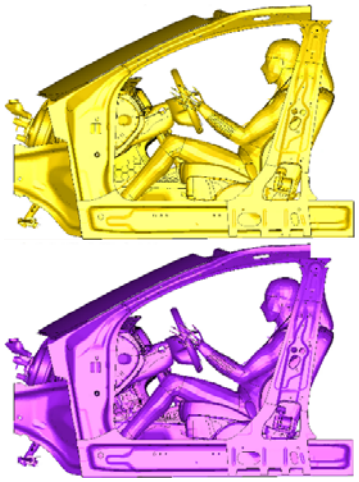

Fig. 7(a). Initial sitting posture; runs 3 (no ERR, *top*) and 4 (ERR, *bottom*).

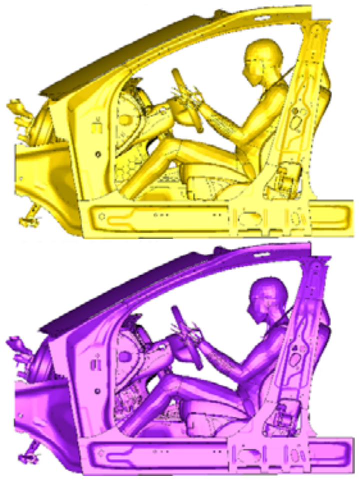

Fig. 7(b). Posture at time of impact (start crash pulse); runs 3 (no ERR, *top*) and 4 (ERR, *bottom*).

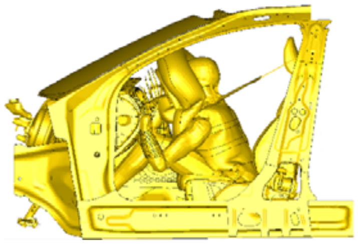

Fig. 7(c). Posture at most forward occupant position for run 3 (no ERR). Run 4 did not reach max. forward occupant position.

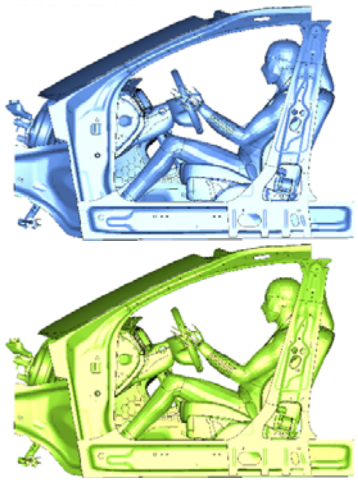

Fig. 8(a). Initial sitting posture; runs 5 (no ERR, *top*) and 6 (ERR, *bottom*).

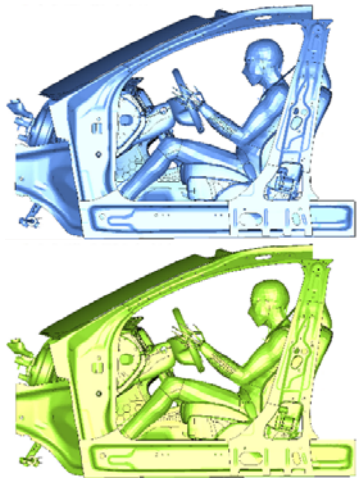

Fig. 8(b). Posture at time of impact (start crash pulse); runs 5 (no ERR, *top*) and 6 (ERR, *bottom*).

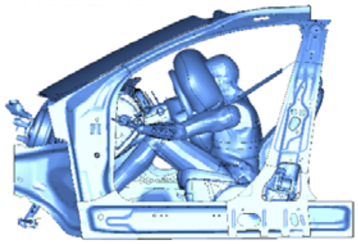

Fig. 8(c). Posture at most forward occupant position for run 5 (no ERR). Run 6 did not reach max. forward occupant position.

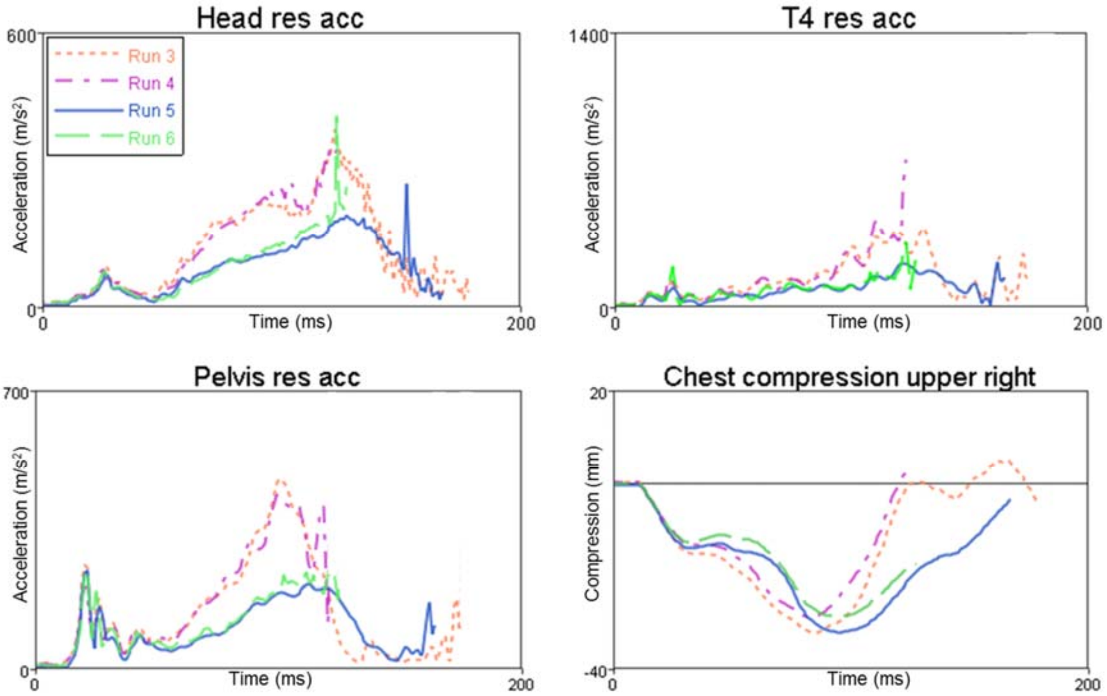

Fig. 9. Occupant responses comparing influence of ERR (runs 4 vs. 3, and runs 6 vs. 5).

IV. DISCUSSION

The initial simulations with the SAFER A-HBM show promising results. Even though involving a complex and lengthy simulation run time, the model is relatively stable, and all except two runs well reached the occupant rebound phase during crash. The two simulations that did not reach rebound terminated within the time of expected maximum occupant injury values. Although the conclusions in this study can be drawn to desired extent, ultimately improved stability is needed. The modelling technique of the active muscles makes them sensitive to changes in set-up. In addition, hands-on adjustments of the THUMS version used was needed, such as adding contacts. The long brake phase results in a significant increase of the simulation time. When using the vehicle model in a typical crash with a crash test dummy, the run time is 1 hour. The same typical crash (including stabilisation phase) with the A-HBM takes 3 hours. If including the long brake phase as well, the total run time is approximately 18 hours. Improving numerical run time would be very beneficial, enabling this tool to be more user-friendly. Improvements, such as implicit calculation, are believed to be favourable, however not fully explored at the moment.

Although not the main purpose of this study, some results from the simulations were achieved. Speed reduction by pre-braking was shown to be beneficial, by substantially reducing occupant accelerations. These results were expected, since the impact speed is reduced. This is evidence of the feasibility of the occupant model as such. From an occupant protection perspective, the findings regarding the effect of pre-braking (with comparable impact speeds) and pre-pretensioning of the seatbelt are more interesting. By using a tool that simulates the whole event, all of the input parameters are included in the analysis. Hence, no additional tests or assumptions are needed to, for example, get a representative occupant posture at time of impact. The results in this study are just a first step, showing positive trends of the feasibility of the model. By varying more parameters, the results will provide more input to vehicle design than can be achieved from this initial study.

The simulations run in this study address occupant protection taking the whole pre-crash and crash sequence into account. The results provide some important insights and are encouraging for further studies. First, the fact that it works as continuous simulations with validated occupant kinematics and responses in both the pre-crash and the crash phase provides a solid foundation for future quality improvements in the development of active safety systems that address occupant protection. Secondly, it is clear that this study does not address some main real-world aspects, such as differences in seating postures and belt slack. By only evaluating occupants in upright sitting posture and perfect seatbelt conditions (without slack), important information is missing. Future studies using the SAFER A-HBM should include slack in seatbelt and different sitting postures, e.g. forward leaning. In addition, different pulse shapes as a complement to brake pulse duration would be valuable to study, enabling additional input to the developments of auto-brake systems.

The SAFER A-HBM used represents a driver exposed to an auto-brake situation. The model can also be tuned to a self-braking driver or a passenger. In addition, future developments should contain variation in occupant sizes and individual characteristics in reactions and muscle tonus, as well as including other pre-crash manoeuvers besides braking. This is challenging from a model development perspective as well as in terms of generating validation data.

This study uses a simple injury assessment through global accelerations and one measure of chest deflection. This was judged sufficient for the purpose of this study, however more sophisticated, still easy-to-use, injury criteria are needed. Especially important is to develop omnidirectional criteria enabling comparisons between different impact directions. The importance of occupant protection driving the developments of active safety technologies calls for an occupant tool that can help to guide the setting irrespective of impact direction, in other words, contrary to the traditional passive safety approach. A human body model with active muscle activation has the best capability to be such a tool.

Using an active human body model provides unique possibilities to evaluate active and passive safety technologies together and their interaction. Specifically in this study, occupant responses in frontal impacts with a preceding event of emergency braking of various characteristics were studied, and the results will help guide the setting of the auto-brake performance.

Given the crash situation is unchanged, the likelihood for a vehicle occupant of sustaining an injury in a crash is reduced in vehicles that are equipped with systems that autonomously brake the vehicle before a crash event [13]. Hence, the reduced impact velocity results in a reduced injury risk. In these cases, additional occupant protection can be achieved if occupant restraints are also initiated in situations in which the vehicle autonomously brakes. Such initiations can be to pre-tense the seatbelts, or to help keep or put the occupant in a good position for optimum response to the protection systems. In an emergency braking sequence, the vehicle occupant can interact with the vehicle interior by resisting the forward motion by tensing the muscles in the body. From a real-world safety development point of view, it is essential to be able to simulate this as well.

The SAFER A-HBM is a unique tool to simulate a braking event with a following crash, adapting its characteristics depending on the sequence of the event. Using a virtual tool enables a real-world realistic comparison of the influence of the parameters studied.

V. CONCLUSIONS

This study shows that an active human body model is both feasible and valuable in developing collision mitigation systems with respect to occupant protection. The SAFER A-HBM was found sensitive to evaluate occupant frontal impact responses after varying auto-brake functionality efficiency. As a first step, two different brake durations, compared to no braking, were evaluated. Occupant accelerations were reduced by 15–45% and 60–70% by pre-braking from 64 km/h to 56 km/h and 39 km/h, respectively. In addition, the effect of an electrical reversible retractor (ERR) were studied. The effect of ERR was not obvious in this study, which is line with expectations, due to the perfect seating position and seatbelt conditions (no slack), conditions in which the benefits of ERR are not pronounced.

Further developments and applications of the active human body model will open up unique possibilities for real-world safety evaluation and will provide an invaluable tool for safety system developments, integrating active and passive safety technologies for enhanced occupant protection.

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VII. REFERENCES

[1] Ljung-Aust, M., Jakobsson, L., Lindman, M., Coelingh, E. Collision avoidance systems – Advancements and efficiency. *SAE World Congress*, 2015, Detroit, USA. SAE Technical Paper 2015-01-1406.

[2] Coelingh, E., Lind, H., Wolfgang, B., Wetterberg, D. Collision Warning with Auto Brake. *FISITA World Congress*, 2006, Yokohama, Japan, Paper No. F2006V130.

[3] Coelingh, E., Jakobsson, L., Lind, H., Lindman, M. Collision warning with auto brake – A real-life safety perspective. *International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2007, Lyon, France, Paper No. 07-0450.

[4] Distner, M., Bengtsson, M., Broberg, T., Jakobsson, L. City Safety – A system addressing rear-end collisions at low speeds. *International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2009, Stuttgart, Germany, Paper No. 09-0371.

[5] Lindman, M., Ödblom, A. *et al*. Benefit Estimation Model for Pedestrian Auto Brake Functionality. *ESAR Conference*, 2010, Hannover, Germany.

[6] Östh, J., Eliasson, E., Happee, R., Brolin, K. (2014) A Method to model anticipatory postural control in driver braking events. *Gait and Posture*, **40**(4): pp.664–9.

[7] Meijer, R., Elrofai, H., Broos, J., van Hassel, E. Evaluation of an active multi-body human model for braking and frontal crash events. *Proceedings of the 23rd ESV Conference*, 2013, Seoul, South Korea, Paper no. 13-0163.

[8] Östh, J., Brolin, K., *et al*. Muscle activation strategies in human body models for the development of integrated safety. *Proceedings of the 24th ESV Conference*, 2015, Gothenburg, Sweden, Paper no. 15-0345.

[9] Schöneburg, R., Baumann, K-H., Fehring, M. The efficiency of PRE-SAFEE systems in pre-braked frontal collision situations. *Proceedings of the 22nd ESV Conference*, 2011, Washington, D.C., USA, Paper no. 11-0207.

[10] Mages, M., Seyffert, M., Class, U. Analysis of the pre-crash benefit of reversible belt pre-pretensioning in different accident scenarios. *Proceedings of the 22nd ESV Conference*, 2011, Washington, D.C., USA, Paper no. 11-0442.

[11] Ólafsdóttir, J. M., Östh, J. K. H. *et al*. Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pre-tensioned restraints. *Proceedings of the IRCOBI Conference*, 2013, Gothenburg, Sweden.

[12] Östh, J., Ólafsdóttir, J. M. *et al*. (2013) Driver kinematic and muscle responses in braking events with standard and reversible pre-tensioned restraints: Validation data for human models. *Stapp Car Crash Journal*, **57**: pp.1–41.

[13] Isaksson-Hellman, I., Lindman, M. Evaluation of rear-end collision avoidance technologies based on real world crash data. *Proceedings of the 3rd International Symposium on Future Active Safety Technology Towards zero traffic accidents, FAST-zero'15*, 2015, Gothenburg, Sweden