# Rear-End Impact Assessment expanded with Pre-Impact Posture Variations

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**Abstract** Present whiplash injury assessment tests, reflecting the seat performance only, provide limited insights into real-world whiplash injury protection needs. Virtual testing of braking followed by a rear-end impact, in addition to alternative initial sitting postures, were conducted to investigate if the current anthropomorphic test device can be used to cover a larger scope of the real-world context.

Reconstruction of published 1.1 g braking volunteer tests showed that a BioRID FE model was capable of recreating human-like kinematics; with head and T1 kinematics just within a 1 SD corridor on the low side of the volunteer response, while vertical displacements and lap-belt forces were underpredicted. A simulation series including pre-impact braking prior to rear-end impact investigated two strategies to vary the backset, as well as pre-impact means of intervention, exemplified by pre-impact seatbelt pretensioning.

Using virtual testing, the study demonstrates examples of expanding the whiplash assessment test setup, enabling inclusion of a variety of occupant sitting postures and a braking event preceding the rear-end impact, while still being feasible to execute. As a next step, a human body model capable of seamless pre-crash and crash prediction could even allow for more in-depth investigations, as well as inclusion of ranges of occupant sizes and posture setting possibilities.

***Keywords*** BioRID FE model, occupant posture, rear-end impacts, virtual testing, whiplash injuries.

## I. INTRODUCTION

Whiplash injuries still represent one of the most significant types of injury in car crashes with respect to both frequency of occurrence and resulting long-term impairment [1]-[2]. Whiplash injuries can take place in all types of crash situations, however the highest risk occurs when a vehicle is impacted from behind [1][3]. In rear-end impacts, whiplash injuries also account for the main part of all injuries.

The first steps in addressing whiplash injuries were taken in the 1970s, with the introduction of head restraints in order to support the head and avoid hyperextension of the neck in rear-end impacts. Real-world follow-up studies confirmed the effectiveness of head restraints [4]-[5]. In the late 1990s further steps were taken when Saab Automobile and Volvo introduced whiplash protection seats: SAHR and WHIPS, respectively. Early on, analysis of real-world accident data confirmed the efficiency of these seats as compared to their predecessors [6]-[7]. This data was used as a benchmark in the development of standardised tests, starting in 2003 with testing by the Swedish Road Administration and Folksam as well as German ADAC, followed by the work by the International Insurance Whiplash Prevention Group (IIWPG) for the Research Council for Automobile Repairs (RCAR) [8]. Resulting dynamic test procedures, for evaluating and rating the ability of seats and head restraints to prevent whiplash injury in moderate and low-speed rear-end impacts (ΔV 16-24 km/h), were later implemented by the Insurance Institute of Highway Safety (IIHS) [9] and European New Car Assessment Programme (EuroNCAP) [10]. Through sled tests, seats are assessed using a mid-size male anthropometric test device (ATD), named BioRID, in one sitting posture [9]-[10]. Following the introduction of rating tests, real-world follow-up studies were made to study the influence on injury reductions in Europe [11] and injury claim rates in the US [12]. It was concluded that seats aimed at preventing whiplash injuries, in general also had lower injury risk in real-world rear-end impacts.

Nevertheless, seat and head restraint designs address only a limited part of the real-world context. First steps towards addressing sitting postures as an aspect for occupant protection in rear-end impacts was taken, through including pre-impact seatbelt pretensioning by activating electrical reversible retractors (ERR), in

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addition to braking and providing warning for the vehicle behind [13]-[14]. Beside these activities, most efforts in the area of whiplash injuries in rear-end impacts concern improvements in seat and head restraint designs, as evaluated in standardised rating tests using a mid-size male ATD in an upright sitting posture. Acknowledging this, consumer information test institutes are exploring means to update their whiplash assessment protocols to include more factors potentially affecting real-world whiplash injury occurrence and means for protection. The IIHS recently announced ambitions regarding varied occupant postures, encouraging robust seat and head restraint designs that can protect many occupants of different sizes and sex, in addition to active safety technologies such as autobrake and evaluation of alternate crash severities [15].

Several factors have been shown to influence risk of whiplash injuries in rear-end impacts, such as individual differences in size, age, sex, sitting postures at time of impact, seat position in the car and impact characteristics [3][16]-[19]. Increased backset (horizontal distance between the head restraint and the back of the head) is one of these factors. Olsson et al. [19] concluded that a backset of 10 cm or more correlates with an increased risk of whiplash injury in rear-end impacts. They investigated 33 occupants by gathering in-depth information on the crash, car and the occupant, including reconstructed backset with the occupant sitting in the actual or similar car. Based on self-reported estimated backset at time of impact, by 1,858 front-seat occupants seated in a WHIPS seat, a steady increase of whiplash injury risk with increased distance was found [17]. Significantly higher average injury risks (61%) were seen for those reporting backset distances of more than 20 cm as compared to those with less than 5cm (22%) for initial neck symptoms and 19% vs 5% for symptoms lasting more than a year.

With the purpose of representing human-like occupant responses including torso-straightening motion in rear-end impact crash tests, the ATD BioRID was developed as a Swedish joint venture during the 1990s [20]. A mathematical counterpart was developed early [21], and several versions of BioRID models have followed. As a complement to the mid-sized male BioRID FE model, the European project ADSEAT developed a mid-sized female FE model counterpart, called EvaRID [22]. There is, however, no physical version of the EvaRID.

Whiplash injuries include a broad set of symptoms, likely caused by multiple injury mechanisms. To capture real-world whiplash injury assessment, it is therefore essential that the assessment criteria address a large spectra of possible injury mechanisms. Some injury criteria candidates have been proposed addressing different injury mechanism hypotheses. The Neck Injury Criterion (NIC) was suggested by [23], derived from a spinal canal pressure gradient theory [24]-[25]. The NIC is based on the relative velocity and acceleration between the upper and the lower neck. In line with the use of upper and lower neck forces and moments for analysing AIS 3+ neck injuries, combinations adapted to whiplash injuries in rear-end impacts have been proposed. Examples include the Lower Neck Load (LNL) index combining forces and moments in the lower neck [26], and $N_{km}$ combining shear forces and bending moments at the occipital condyles [27]. When developing the WHIPS seat, the real-world challenges of the range of injury mechanisms and the varieties in occupant sizes and sitting postures were addressed through the following guidelines: reduce the overall acceleration, minimize relative spinal movement and reduce forward rebound [3]. Translated into injury assessment measures, the relative movements throughout the whole spine were focused, in addition to reducing overall occupant acceleration [28]. This approach was found successful, shown by real-world whiplash injury reductions [7][29]. The current assessment criteria in the standardised rating tests have been set based on best practice using testing of benchmark seats [9]-[10]. This approach results in assessment criteria not necessarily addressing the injury mechanisms causing whiplash and is also dependent on the test setup.

Present standardised whiplash injury assessment tests provide limited insights into real-world whiplash injury protection needs; by reflecting the seat and head restraint performance only, without taking the car design, other restraints nor the pre-impact situation into account, and one occupant size only. This study investigates the opportunities of expanding the current sled test setup while still maintaining the feasibility to execute it. With the purpose to explore if the current ATD (BioRID) can be used to cover a larger scope of the real-world context, the aim was to investigate virtual testing of braking followed by a rear-end impact, and alternative initial sitting postures. Specifically, the aims were to assess the BioRID model’s ability to predict car occupant kinematics during braking interventions, and in addition to investigate two strategies to include variation of backset in virtual seat testing, as well as inclusion of pre-impact means of intervention, exemplified by seatbelt pretensioning.

## II. METHODS

Two simulation series with the FAT BioRID v3.9 Finite Element (FE) ATD model (Dynamore GmbH, Stuttgart, Germany) were conducted, in addition to two tests with the physical BioRID. The BioRID FE model was positioned in a sled with a Volvo WHIPS generation 2 front seat [14] FE model, with a reference position of 35 mm backset. A three-point seatbelt model with a prototype ERR functionality able to pre-tension the seatbelt was used. The BioRID model was positioned using pre-simulation followed by seat-squashing in ANSA (Beta CAE Systems, Luzern, Switzerland) and subsequent stress-initialization using a reference geometry for the seat foam. A penalty-based contact with a friction of 0.5 was used between the ATD and seat, and 0.4 between ATD and seat belt. All simulations were made using LS-DYNA MPP R9.3.1 (LSTC, Livermore, CA, USA).

The first simulation series was made to assess the ability of the BioRID model to predict car occupant kinematics during braking interventions. The simulations were compared with published volunteer data. In the second simulation series, rear-end impacts in combination with preceding brake interventions, were conducted to investigate the opportunities of expanding the test setup. Brake pulse, sitting postures (forward leaning) and seatbelt pretensioning were varied. Data from physical tests were included to provide a first insight into the physical ATD's capabilities in this context.

### *Assessing Ability of simulating Braking Kinematics*

Simulations corresponding to volunteer tests [30] were carried out, to assess the ability of the BioRID FE model to predict car occupant kinematics during braking interventions. Ólafsdóttir et al. [30] conducted a volunteer test series comprising 11 male subjects with an average male anthropometry in a car front passenger seat. The seat in the volunteer study was positioned in the mid fore-aft position at mid height, and volunteers had their hands on their lap and sat in a relaxed riding posture. The FE simulation seat model was similarly adjusted, however it was of a later generation Volvo front seat compared with the one in the volunteer study [30]. The volunteer test seat was evaluated for cushion stiffness [31] and quasi-static linear stiffnesses for the front and rear part of the cushion were 17 N/mm and 21 N/mm, respectively. The FE seat model used in the present study was found to have a cushion front stiffness of 21 N/mm and rear stiffness of 17 N/mm, respectively, i.e., of similar magnitude but not the same exact distribution front and rear. In addition to a similar seat and seatbelt position compared with the volunteer test, a foot well surface was positioned under the feet of the BioRID model.

In the volunteer study [30], the volunteers were subjected to repeated 1.1 g brake interventions with a standard three-point seatbelt with and without an ERR with a force of 170 N, applied in a randomised order. Both these conditions were simulated by application of the average acceleration pulse from the braking interventions in the volunteer tests. The simulation time was 2200 ms after an initialisation time of 300 ms to settle the BioRID model in the seat. Due to the high number of cycles, these simulations were run using double precision LS-DYNA.

BioRID head rotation, head centre of gravity and T1 X and Z displacement data was compared to the average volunteer responses and one Standard Deviation (SD) corridors, together with shoulder belt, lap belt and footwell boundary condition forces. CORA analysis was done using CORAplot 4.0.4 (PDB, Gaimersheim, Germany) utilising the one SD corridors from the tests as the inner corridor, and a two SD wide outer corridor. This is in accordance with [31] who compared an active human body model (AHBM) to the same volunteer tests.

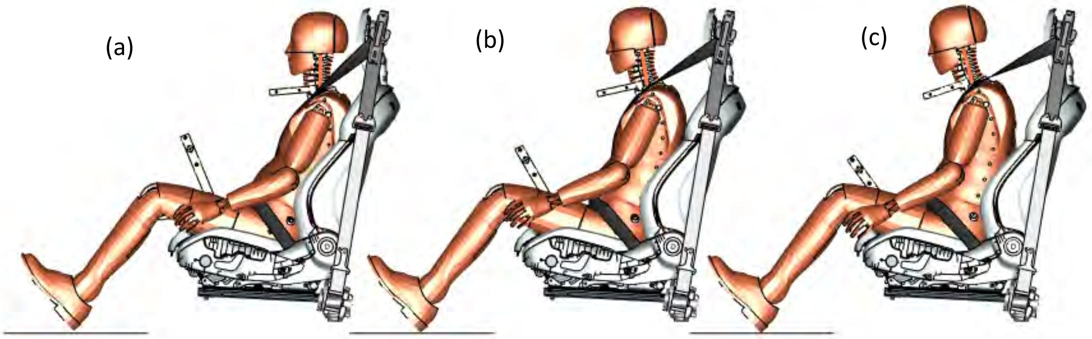

Fig. 1. The BioRID model positioned in a Volvo WHIPS generation 2 front seat model: reference position with a backset of 35 mm (a), and forward leaning with backsets of 130 mm (b) and 200 mm (c).

### Expanded Test Setup

The sled with the BioRID model was used in eleven simulations with the EuroNCAP mid-severity rear-end impact pulse with a $\Delta V$ of 16 km/h, Table I. Eight simulations were performed with a preceding brake pulse at 0.5 g (medium) or 1.1 g (harsh) for 800 ms, with the BioRID model in the reference position initially. The harsh brake pulse was characterised by a deceleration rate of 67 $m/s^3$ from approximately 150–300 ms and then reaching an average of 1.1 g. The medium brake pulse was achieved by scaling the harsh brake pulse by 0.45. Each braking level was simulated without ERR activation or combined with an ERR shoulder belt force of 150 N, 300 N, and 600 N. In addition to this, three simulations were performed without any brake pulse prior to the rear-end impact. For two of these the backset was varied, as shown in Fig. 1, to represent the backsets reached in the two braking simulations without ERR activation (Simulations 1 and 5).

The BioRID model was positioned in the seat model with its H-point 20 mm forward and 4.5 mm downward of the SAE-manikin H-point location. In all simulations the arms were close to the torso with the hands on the side of the thighs at the edge of the seat cushion, Fig. 1. For the reference position, the pelvis angle was 26.5° and for the simulations with a larger backset at the start of the simulation, the BioRID model was positioned using rigid body rotation around the pelvis, decreasing the pelvis angle to 19° and 13.1° for an initial backset of 130 mm and 200 mm, respectively. A pre-simulation was also run to adjust the flexion of the upper legs to position the feet on the floor and to rotate the legs inward by 1.5° to reach a knee to knee distance of 200 mm for all positions.

TABLE I
SIMULATION AND TEST MATRIX

| Simulation / Test | Brake pulse | ERR Force | Backset at start (mm) | Backset at impact (mm) |
|---|---|---|---|---|
| *Simulation 1* | Medium (0.5g) | No ERR | 35 | 130 |
| *Simulation 2* | Medium (0.5g) | 150 N | 35 | 69 |
| *Simulation 3* | Medium (0.5g) | 300 N | 35 | 54 |
| *Simulation 4* | Medium (0.5g) | 600 N | 35 | 41 |
| *Simulation 5* | Harsh (1.1g) | No ERR | 35 | 200 |
| *Simulation 6* | Harsh (1.1g) | 150 N | 35 | 118 |
| *Simulation 7* | Harsh (1.1g) | 300 N | 35 | 92 |
| *Simulation 8* | Harsh (1.1g) | 600 N | 35 | 77 |
| ***Simulation 9 (reference)*** | No braking | No ERR | 35 | 35 |
| *Simulation 10* | No braking | No ERR | 130 | 130 |
| *Simulation 11* | No braking | No ERR | 200 | 200 |
| *Physical Test 1* | No braking | No ERR | 275 | 275 |
| *Physical Test 2* | No braking | 230 N | 275 | 110 |

In addition to the simulations, two physical tests were performed with the BioRID in a Volvo WHIPS generation 1 seat, Fig. A6 in the Appendix. The same rear-end impact crash pulse as in the simulations, but without preceding braking, was used. The BioRID was positioned in a forward leaning posture, by forced rotation around the hip, changing the pelvis angle to achieve the target backset of 275 mm. In one of the tests, the ERR was activated with 230 N, 1000 ms prior to the impact with the sled stationary, reducing the backset prior to impact.

### Data Processing

Kinematics data from the simulations were extracted from the head centre of gravity and the position of the T1 and pelvis accelerometers in the ATD. Head and T1 accelerations were filtered with a CFC 30 filter for both simulations and tests, and the T1 acceleration presented is the average of the two T1 accelerometers of the BioRID. Upper neck forces and moment were filtered with a CFC 600 filter for both simulations and tests. NIC was calculated according to Eq. 1 [23]:

$$NIC = 0.2a_{rel}+v_{rel}^2 \tag{1}$$

in which $a_{rel}$ is the relative X-acceleration between the head and the average of the two T1 accelerometers of the BioRID, and $v_{rel}$ is the relative velocity between head and T1 integrated from the acceleration signal.

## III. RESULTS

### *Ability of simulating Braking Kinematics*

Head and T1 X displacements for the BioRID model compared with the response of volunteers in the braking interventions were on the lower margin of the 1 SD corridor, Fig. A1 in the Appendix, and resulted in CORA scores of 0.8/0.82 for the head and 0.66/077 for T1 in the simulations without ERR and with 170 N ERR test conditions, respectively, Table I. Z displacements had a lower CORA score, due to limited upward movement of the BioRID model. The BioRID model had higher footwell forces than the volunteers and thereby lower lap belt forces, resulting in lower CORA scores for these boundary condition forces than for the shoulder belt which matched that of the volunteers well, Fig. A2 in the Appendix. The BioRID peak backset was 185 mm without ERR, and 111 mm for the 170 N ERR condition, during the steady state braking.

TABLE II

CORA SCORE FROM SIMULATIONS OF BRAKING INTERVENTIONS WITH VOLUNTEERS [30] AND WITH THE BIORID FE MODEL.

| | Head X | Head Z | Head Rotation | T1 X | T1 Z | Shoulder Belt Force | Lap Belt Force | Footwell Force | Overall |
|---|---|---|---|---|---|---|---|---|---|
| *Braking without ERR* | 0.80 | 0.56 | 0.87 | 0.66 | 0.24 | 0.85 | 0.72 | 0.44 | 0.64 |
| *Braking with 170 N ERR* | 0.82 | 0.91 | 0.74 | 0.77 | 0.50 | 0.90 | 0.52 | 0.43 | 0.70 |

### *Kinematics due to Braking Intervention*

The braking interventions positioned the BioRID's head forward, from the initial reference position of 35 mm, prior to the start of the rear-end impact. In the harsh braking event, the head moved up to 165 mm forward; resulting in a backset at the start of the rear-end impact of 200 mm without ERR activation, and backsets of 118 mm, 92 mm and 77 mm, respectively, with increasing ERR force, see Fig. 2 and Table 1. The corresponding resulting backsets for the medium brake pulse, at time of rear-end impact, were 130 mm (no ERR) and 69 mm, 54 mm and 41 mm, respectively.

During all the pre-impact braking simulations, T1 and pelvis moved downwards (Fig. 2). The higher the ERR force, the larger the downward movement: for an ERR force of 600 N it was 23–24 mm, compared to 15 mm with a standard belt, for both T1 and pelvis, respectively. The peak rearward movements of T1 and pelvis were also equally large for medium and harsh braking events when 600 N ERR force (24–27 mm) was applied. The larger downward movement with higher ERR force was due to the wrapping of the belt over the shoulder: with higher ERR force, a portion of the belt force pushed the ATD model downwards. With an ERR force of 300 N and 600 N some rearward movement of the BioRID was seen for the T1 X-displacement, meaning that the ERR activation did not only prevent forward displacement, it also moved the torso of the BioRID rearward before the start of the rear-end impact.

The activation timing of the ERR belt force was fast in the simulation model and reached the target force in about 10 ms, Fig. 3. The shoulder belt force was later increased additionally, when BioRID started to move forward due to the braking pulse.

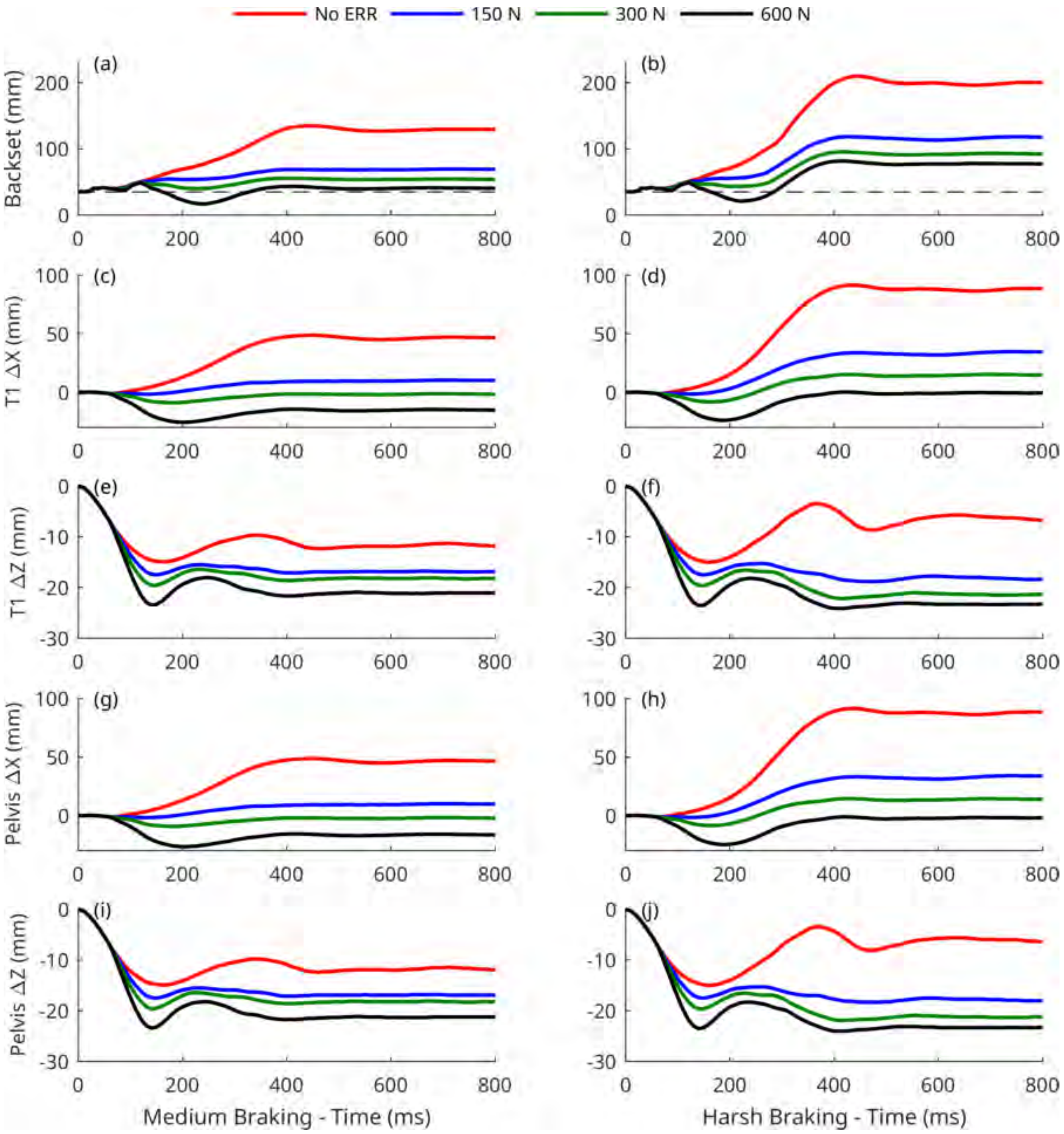

Fig. 2. BioRID kinematics in the braking simulations with and without ERR, preceding the impact. Thin grey dashed line for backset graphs indicates the initial backset of 35 mm.

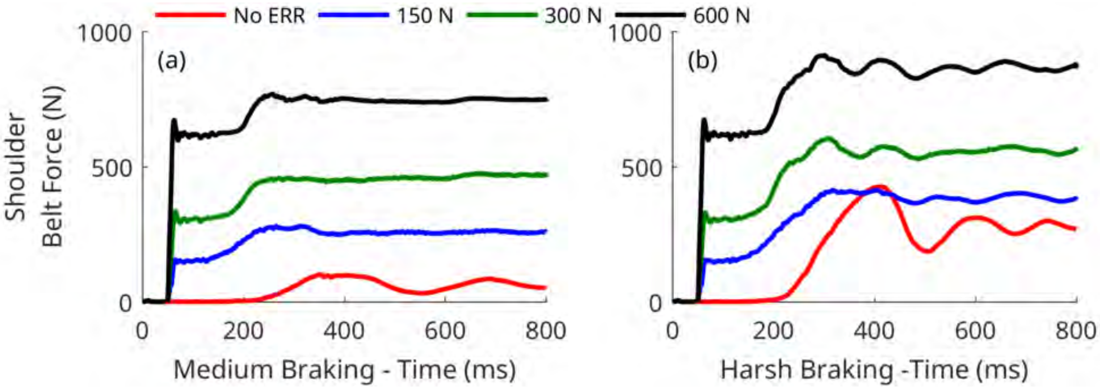

Fig. 3. Shoulder belt forces in pre-impact braking simulations with and without ERR activation.

***Influence of Pre-Impact Braking Intervention and ERR***

By comparing the rear-end impact simulations with the pre-impact braking without ERR force (Simulations 1 and 5) and the pre-positioned non-braking simulations with the corresponding backsets (Simulations 10 and 11), the influence of the dynamic repositioning during pre-impact braking interventions can be evaluated.

The BioRID kinematics during the impacts, Fig. 4, show that the largest initial backsets also gave the largest displacements of the head, T1 and pelvis. As the BioRID got a higher speed relative to the seat, it resulted in larger deflection of the seat and thereby higher rearward displacements. For the simulations with the varying ERR forces during the pre-impact braking event this effect was not as large, due to restraint of the torso and more similar backsets at impact, whereby similar peak deflections were seen for those simulations, Fig. 4. The larger initial backset also resulted in larger differences in peak displacement in time between the head, T1 and pelvis, indicating more even relative internal spine movements. Fig. A3 in the Appendix shows an illustration of the BioRID trajectories in the rear-end impact phase comparing the relative position of head, T1, T8, L1 and pelvis at time of impact and at peak head excursion.

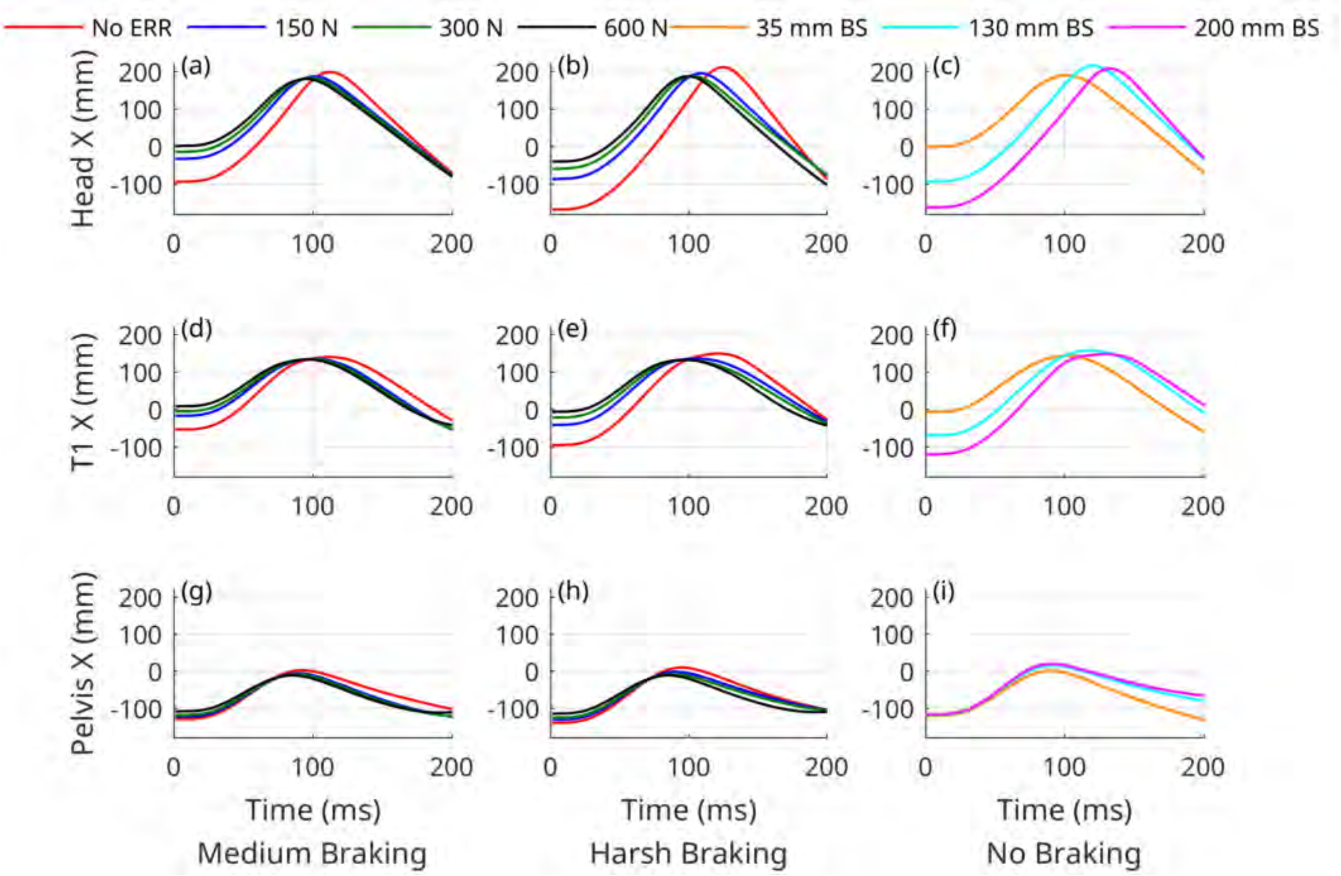

Fig. 4. Head, T1, and pelvis X displacement over time relative to the position of the back of the head for the reference simulation with 35 mm backset (orange in panel (c)), in the rear-end impact phase of the simulations with pre-impact braking and in no braking simulations with pre-set backsets (BS).

Although somewhat different T1 and the pelvis starting positions at impact, head X-accelerations, including peak values, were similar for simulations with similar initial backset, Fig. 5. For example, the medium brake pulse simulation without ERR led to a backset of 130 mm and a peak head X-acceleration of 28.2 g, while the 130 mm pre-positioned backset simulation (without braking) had a peak head X-acceleration of 28.4 g. Same similarities were seen for the head X-acceleration in the simulations with harsh brake pulse, while less evident for T1 X-acceleration, especially regarding peak values.

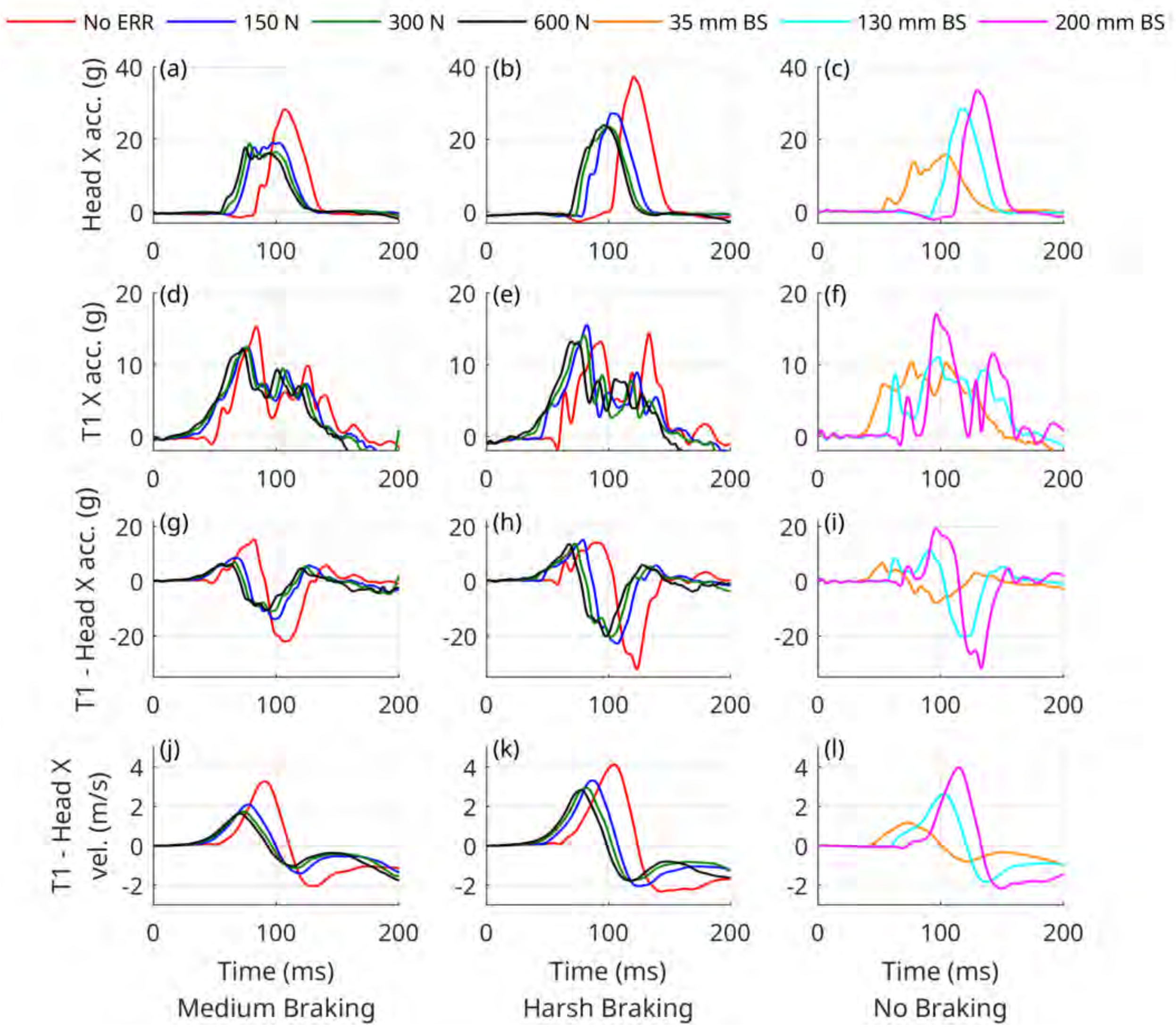

Fig. 5. Head X-, T1 X-, T1 − Head X acceleration (acc.) and T1 − Head X velocity (vel.) in the rear-end impact phase of the simulations with pre-impact braking and in no braking simulations with pre-set backsets (BS).

Overall, the efficiency of the ERR in reducing pre-impact forward movement was reflected in the head and T1 in-crash kinematics, by earlier acceleration response and lower peak values, as compared to the simulations without ERR, Fig. 4 and Fig. 5. However, there was no large effect with increasing the level of the ERR belt force. For the medium braking simulations, all three ERR force levels led to a reduction of peak head X-acceleration to approximately the same magnitude (17.7–19.0 g). A larger variation was seen for the harsh braking simulations, however not consistent with respect to ERR force level influence simulations (27.2 g, 23.4 g, 23.9 g for 150 N, 300 N, and 600 N, respectively). The difference between T1 – head X acceleration and velocity, showing the relative movements between head and torso, reflected partly the same trends, Fig. 5. Comparison of the T1-head X acceleration of the three ERR simulations of medium brake pulse to the reference simulation showed comparable magnitudes (6.3-8.5 g and 6.7 g, respectively). However, this was not seen for the harsh braking simulations. The amplitude of the initial maximum values of these measures were both related to the backset at impact. NICmax, which also reflect head relative to T1 movements, was also seen related to the extent of backset at time of impact, see Fig. A4 in the Appendix.

The upper neck loadings show the same trend as the head and T1 acceleration; a larger backset at the start of impact results in higher forces and moments, and the ERR activation was efficient in reducing the loads, see Fig. A5 in the Appendix. The initial upper neck shearing force $F_x$ was offset in the simulations with pre-impact braking due to the brake pulse loading, −20 and −50 N for medium and harsh braking, respectively. Due to this offset, the upper neck $F_x$ force remains negative for the whole rear-end impact for all the harsh braking simulations (except for a peak force of 1 N for the simulation with 150 N ERR force). Increasing backset leads to a higher peak upper neck $F_z$ tension force, highest at 949 N for the harsh pre-impact braking simulation without ERR force. Upper neck $M_y$ moments were affected by the change in backset, but the range of peak values for all simulations limited to 8.4–15.3 Nm.

The two physical crash tests provided insights into some of the aspects seen in the simulation series. Similar to the simulations, the 230 N ERR activation led to a reduction in backset (from 275 mm to 110 mm), which also led to a considerable reduction in peak accelerations as compared to the test without ERR activation, Fig. A7 in the Appendix. Head peak X-acceleration was reduced from 23.5 g to 17.0 g, and the peak T1−Head X acceleration from 8.4 g to 7.7 g, while the reduction in peak T1−Head X velocity was larger, from 5.1 m/s to 2.9 m/s. A substantial reduction in upper neck $F_z$ was also seen, Fig A8 in the Appendix.

## IV. DISCUSSIONS

This study evaluated an FE model of the BioRID ATD with respect to its kinematics in braking events and studied a combination of pre-impact braking and rear-end impact which could be used to expand current rear-end impact test protocols to cover a larger part of real-world accident scenarios. Pre-impact braking displaces the occupant forward, increasing the backset between the head and the head restraint. Backset at impact, is related to increased injury risk, irrespective of size of occupant and reason for this increased backset [17]-[19]. Whiplash injury mitigation technologies today include more than the seat and head restraint design, exemplified by pre-impact positioning using the seatbelt [13]-[14]. In line with this, the consumer information test institutes are exploring means to update their whiplash assessment protocols [15].

The present study shows that it is possible to extend current standardised whiplash test procedures with a dynamic pre-impact phase in the form of braking, e.g., Autonomous Emergency Braking, or represent the outcome of such an event by positioning the BioRID in a forward leaning posture. In both the pre-positioned simulations and the simulations including the pre-impact braking, an increased backset resulted in more extensive relative displacements, also reflected in accelerations and forces. This is in-line with the increased injury risks with increased backset seen in real-world traffic [17]-[19], irrespective of the reason for the increased backset. Extending the standardised test procedure by including a variety of sitting postures, is in line with the real-world evidence of the importance of addressing backset at time of impact.

The simulated braking interventions positioned the BioRID model more forward. When comparing the pre-impact braking initiated forward leaning postures to the corresponding position by pre-setting the BioRID model prior to the rear-end impact, no considerable differences in kinematics and responses were seen during the rear-end impact phase. It was mainly the difference in the position at impact, rather than the dynamic repositioning as such, that affected the outcome in the rear-end impact. Furthermore, no major differences could be assigned to the initial difference of vertical position of the T1 and pelvis at time of impact, as a result of the belt pretensioning. The seat used in the simulation series is designed to provide an even support for the whole spine, accounting for different sizes of occupants [14]. Hence, additional simulations with different types of seat designs are recommended before conclusions can be drawn about the influence of this difference in torso position at impact, on a wider basis.

By including the braking prior to the rear-end impact, it was possible to evaluate the effect of seatbelt pretensioning by the ERR. The ERR activation reduced the dynamically induced increase in backset during braking, having positive impact on both kinematics and loadings in the rear-end impact. With the highest ERR forces it even moved the torso of the BioRID model rearward before time of impact, which enhanced the protection by reducing initial backset. However, it should be noted, that even with high levels of ERR activation there will be an increase in backset during braking deceleration as the head still moves forward relative to the torso and this is not negated by the activation of the ERR.

The capability of the ERR to reduce the forward movement of the BioRID model in the simulations, and even pull back, was also reflected in the physical tests. The ERR activation in the physical test reduced the backset by 165 mm prior to impact. A few studies have looked into human behaviour in relation to repositioning during static conditions [32]-[33], although more studies are needed to validate the physical as well as the virtual BioRID for ERR retraction in forward leaning postures. Lorenz et al. [32] tested activation of an electrical pretensioner in a stationary vehicle using volunteers of varied sizes, whereof some were in forward-leaning positions. Develet et al. [33] performed similar tests using mid-sized male volunteers and two ATDs, in three different forward-leaning postures. Each volunteers' chest and head were moved towards the seat and in more than half of the cases, the head was in contact with the head-restraint. The BioRID did not show sufficiently large rearward motions nor head rotations to fit the corridors of the volunteers [33].

Injury criteria for whiplash injuries are still not well established. The criteria used in the standardised rating tests are based on best practice using benchmark seats more than 15 years ago [9]-[10]. Although NICmax has its foundation based on a theoretical injury mechanism, several of the other performance measures do not. As examples, the *time to head restraint contact* as well as the limits for neck forces and moments used in the rating protocols today are based on benchmark tests, i.e., test comparing seats of different performance. These tests were performed with the ATD in the upright sitting posture as included in the rating tests today, whereby it should be ascertained whether they are applicable if applied in a different context, as studied herein. Simply, when changing test setups, work is required addressing the injury measures to be evaluated. The proposed way forward is to focus the kinematics and select injury measures to reflect preferred kinematics. The approach as addressed in [28], focusing on the whole spine and to minimise its relative movements, in addition to reducing overall occupant acceleration, is an example of this way of working.

The BioRID FE model used for this study, the FAT v3.9 model, has been validated at component, subsystem and complete dummy level compared with tests with physical BioRID and BioRID parts [34] and shows a close correlation with respect to the physical test data. In this study, the model's use was extended outside its intention and validation. Nevertheless, it is reasonable to believe that the general findings of this study, exemplified by the effect of the ERR activation to help reduce the dynamically induced backset during braking and that this increase correlates with that of human volunteers, should be valid also for physical BioRID ATDs.

Although not developed for braking events, the BioRID model's kinematics corresponded well with the volunteer data in the 1.1 g brake events studied and showed itself sensitive to the ERR activation. The simulations of the volunteer tests to assess the BioRID model's ability to predict car occupant kinematics during braking interventions resulted in CORA values of 0.8/0.82 and 0.66/0.77 for the head and T1 X displacement (Table II) in tests without and with ERR, respectively. The higher score for the head was the effect of the BioRID response falling just inside the lower boundary of the volunteer 1 SD corridor, while for the T1 displacement the curve was just outside for more samples and the CORA score went down. These forward displacements are the most important predictions in the braking event when followed by a rear-end impact, as they determine the backset at the start of the rear-end impact. The head X displacement CORA score was fairly high, due to it just making the 1 SD corridor, but also because the shape and phase matches that of the volunteers well (this is largely determined by the braking pulse). This is an indication that using the BioRID in a combination of pre-impact braking and rear-end impact is feasible. It should be noted that the prediction by the BioRID is on the lower end of the response spectrum, though. With the head forward displacement on the lower bound of the 1 SD corridor, 84% of 50th percentile male occupants would have head forward displacements larger than predicted by the model.

There was a difference in the T1 vertical movement between the simulations made to assess the BioRID's ability to capture occupant braking kinematics and when the model was applied in combination of braking and rear-end impact. For the simulations of the volunteer tests, almost no vertical movement was found in the ATD response (Fig. A1 in the Appendix), while in the simulations with braking and rear-impact at least 10 mm downward movement was found for the pelvis and T1 (Fig. 2), and increasing with increasing ERR pre-tension. This difference is most likely caused by the lack of a foot well surface in the application simulations, allowing some more movement of the pelvis.

Larsson et al. [35] simulated the same volunteer test setup as in this study, but with an AHBM, and found overall combined CORA scores of 0.81 and 0.82 for the tests with and without pretensioner scenarios, respectively, while the BioRID model scored 0.64 and 0.7. The AHBM scored higher for head and T1 X displacement, but lower for head rotation than the BioRID model. The AHBM also had a correlation above 0.85 for the boundary condition forces, while the BioRID model had an imbalance in the footwell force and lap belt force, compared with the volunteers. It appears that the BioRID has higher reaction forces for the legs and feet, thereby reducing the lap belt load. If the ATD is also stiffer than the volunteers when it comes to rotation around the hip, would explain why it was at the lower margin of forward head and T1 X displacements. For simulation studies, an AHBM such as described by [35] is a better occupant surrogate than the BioRID ATD model. Therefore, for future virtual testing assessment protocols, the use of an AHBM with tissue level injury prediction is likely a more precise tool than the BioRID. Development of HBMs for this purpose are underway

[35], but not yet mature. HBMs are also better tools with respect to recreating a variety of occupant sizes and shapes. Work for this purpose is also underway [37], although not yet widely available.

The two brake pulses in the second simulation series were chosen to reflect different acceleration levels. The harsh brake pulse of 1.1 g is of similar acceleration level as the brake pulse used in the first simulation series, resembling the autobrake pulse in the volunteer study [30]. In the corresponding volunteer study for the driver position, the manual harsh braking pulses were similar to the autobrake pulse [31], confirming that the brake pulse selected is representative for a harsh manual braking. The medium brake pulse was scaled from the harsh pulse to be more representative of a moderate brake scenario, being more frequent in real-world situations.

The pre-set backsets in this study, chosen as a result of the braking event, are within the range of reasonable real-world head positions, also when without pre-impact braking. Jonsson et al. [38] measured head positions of 65 female and male drivers in a WHIPS seat, with the car stationary and while driving four different routes. While the female average backsets varied from 32 mm (SD 22 mm) when stationary, and from 66 mm to 85 mm (SD 29 mm) during the four routes, the corresponding male average backsets were 74 mm (SD 34 mm), and 104 mm to 132 mm (SD 48 mm). Urban driving produced a larger backset compared to driving in more rural conditions [38].

The braking effect on posture is one of the main arguments to include braking as a dynamic event in the assessment method, by then making it possible to include any pre-impact activated countermeasures as part of the occupant protection strategy. This study provides evidence that this is feasible with the available ATD, and also by implementing it as a virtual assessment method. Virtual tests can also allow for inclusion of more parameters than possible in physical tests. It allows for a larger variation of crash pulses, and could even enable the use of vehicle specific crash pulses, to also reflect the differences in car body design or other countermeasures addressing the rear-end impact crash pulse. Including a vehicle specific crash pulse will enhance the assessment method further, also making it more in-line with the assessment methods for frontal and side impact evaluations, in which the whole vehicle is engaged.

Today, standardised rear-end impact crash tests for whiplash injury assessment provide limited insights into real-world protection needs. They reflect the seat performance only, without taking the car body design, restraints beyond the seat, nor the pre-impact situation into account. Using an available virtual ATD, this study suggests that the scope can be widened to include a braking intervention preceding the rear-end impact. More so, the standardised test methods reflect a one-size occupant in one sitting posture. The present study provides input to expand towards more sitting postures, in addition to the influence of pre-impact restraint activation. Additionally, when moving towards virtual testing it opens for inclusion of a variety of occupant sizes and adaption of vehicle crash pulses coming even closer to the real-world context of whiplash injury occurrence in real-world traffic, and still being feasible to execute.

## V. CONCLUSIONS

The BioRID FE model was found capable of recreating human-like kinematics, also when subjected to 1.1 g braking, which could occur prior to a rear-end impact. Head and T1X displacement, being the most relevant for rear-end impact simulations with the BioRID, were just within but on the lower boundary of a 1 SD corridor around the volunteer response and showed CORA values of 0.8/0.82 and 0.66/0.77 for tests without and with ERR, respectively. The Z-displacements and lap-belt forces were underpredicted.

The model was shown sensitive to differences in sitting postures and seatbelt ERR force levels. Promoting robust seat and restraint designs, that can protect occupants in a variety of sitting postures, is in line with the real-world evidence of the importance of addressing the backset at time of impact. The study demonstrates examples of expanding the whiplash assessment test setup, enabling assessment for a variety of occupant sitting postures including a braking event preceding the rear-end impact, while still being feasible to execute. Virtual testing with the BioRID model was used in this study. As a next step, a human body model capable of seamless pre-crash and crash simulation could allow for even more in-depth investigations, as well as inclusion of more occupant sizes and posture variation possibilities.

## VI. ACKNOWLEDGEMENT

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## VIII. APPENDIX

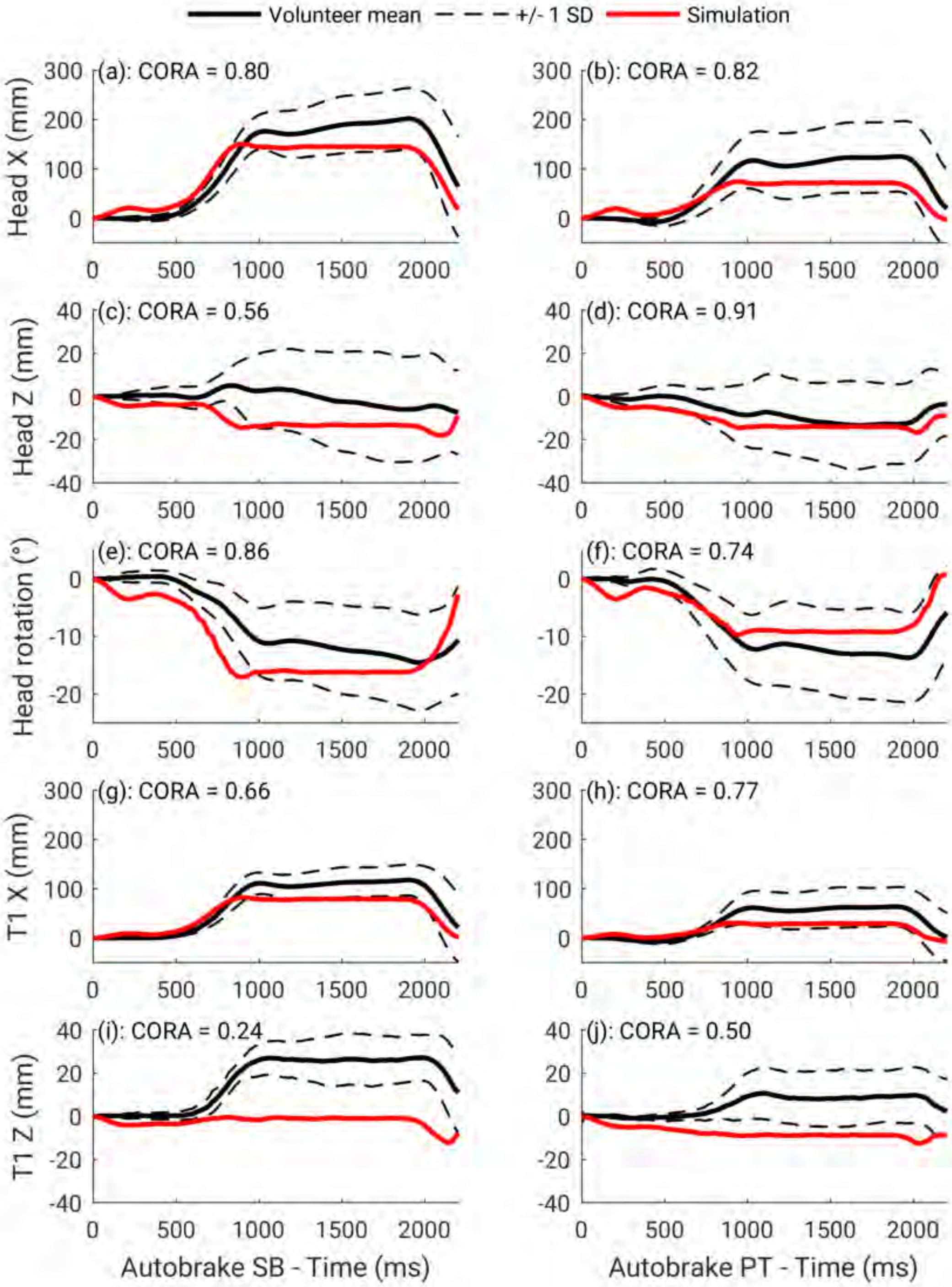

Fig. A1. Kinematic time history data from volunteer tests with 1.1 g braking interventions [30] and simulation results with the BioRID FE model.

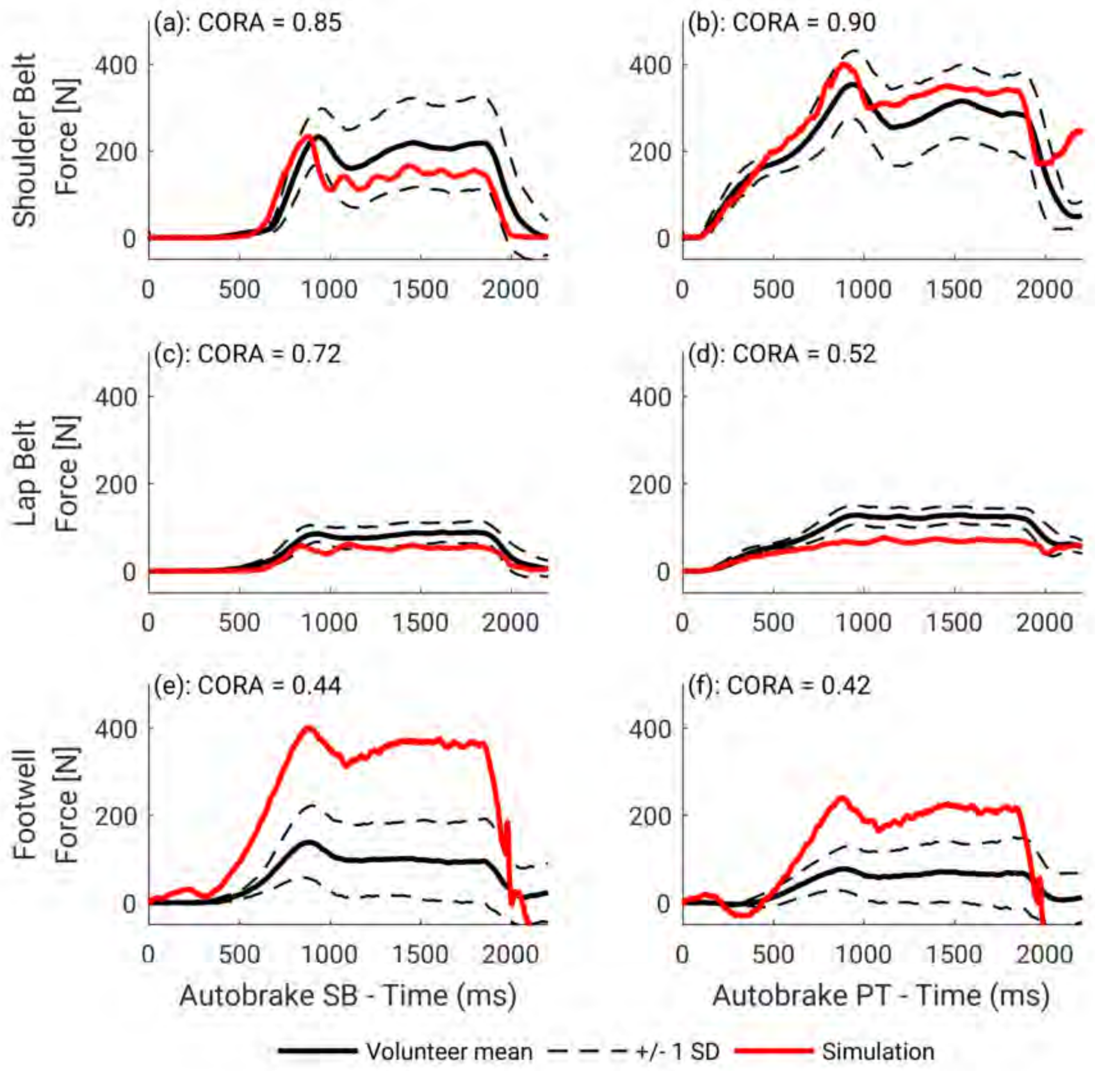

Fig. A2. Boundary condition time history data from volunteer tests with 1.1 g braking interventions [30] and simulation results with the BioRID FE model.

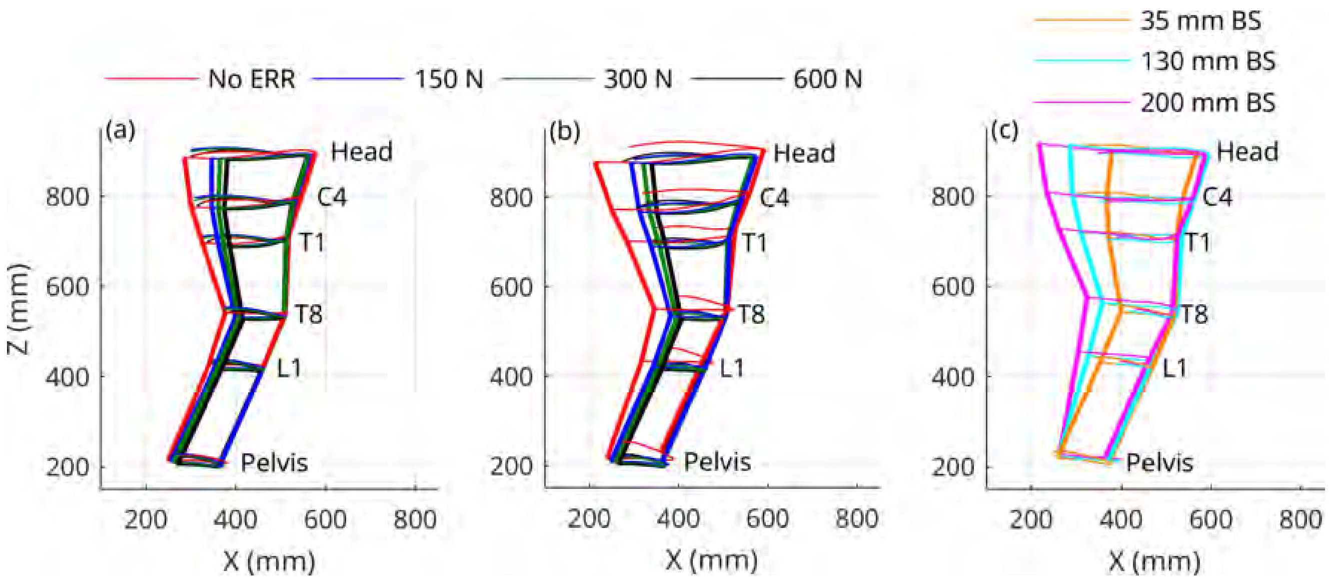

Fig. A3. BioRID trajectories in the rear-end impact phase of the simulations; medium braking (a), harsh braking (b) and no braking with pre-set backsets (BS, c). The thick solid line to the left shows the position at time of impact and the solid line to the right the position at peak head excursion.

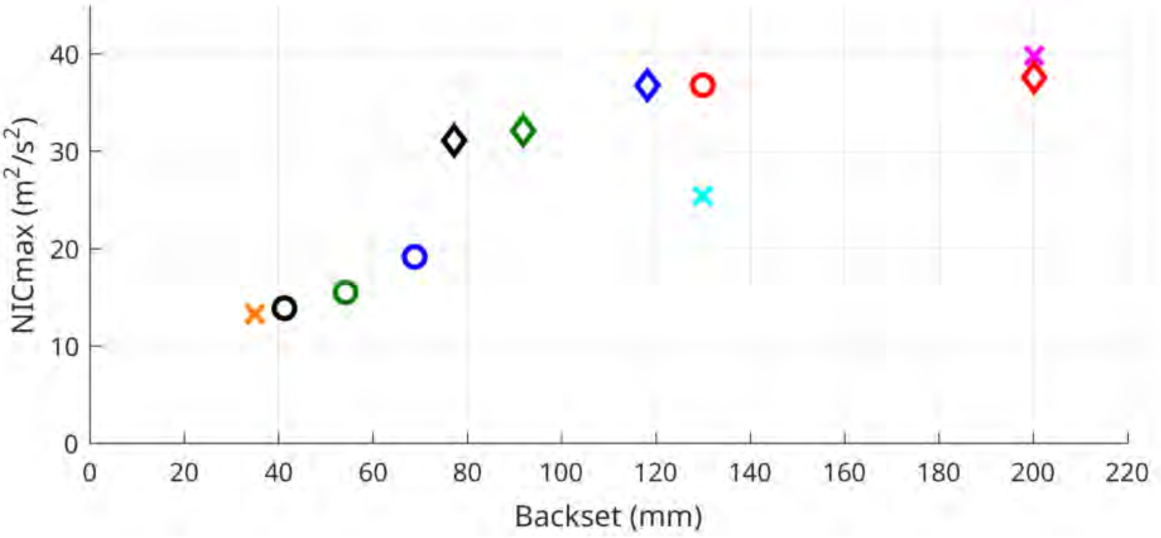

Fig. A4. NICmax vs backset at impact. Medium braking simulations indicated with circles, harsh braking with diamonds and the three simulations without preceding braking are marked with X.

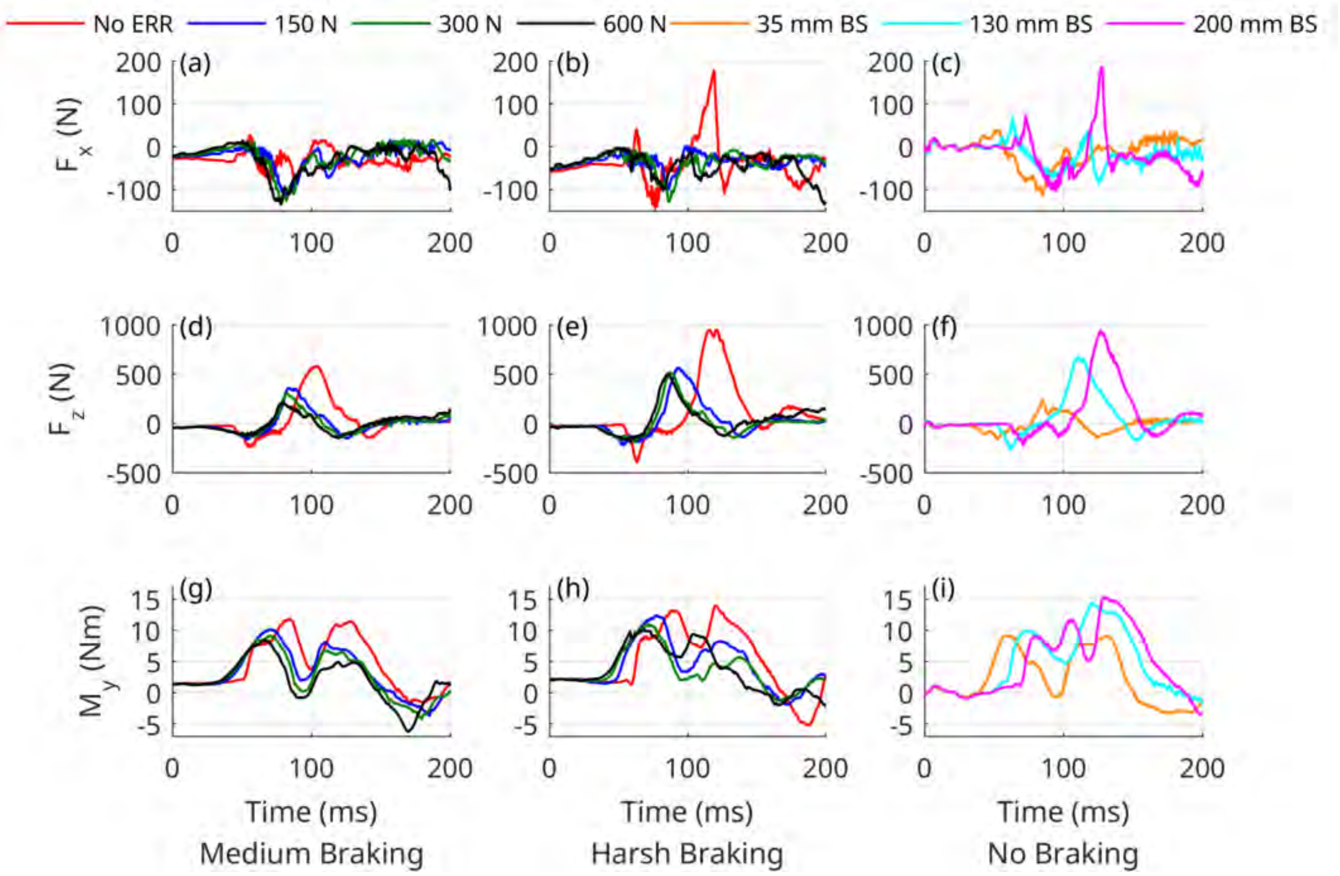

Fig. A5. Upper neck $F_x$, $F_z$ and $M_y$ in the simulations with pre-impact braking and in no braking simulations with stationary increased backset (BS).

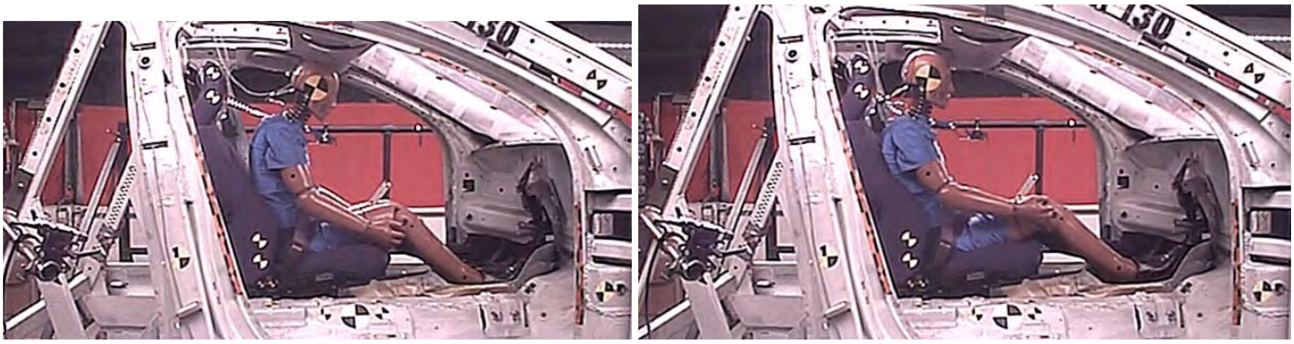

Fig. A6. BioRID II ATD positioned with 275 mm backset in physical tests (left), and with a backset of 110 mm (right) after ERR activation.

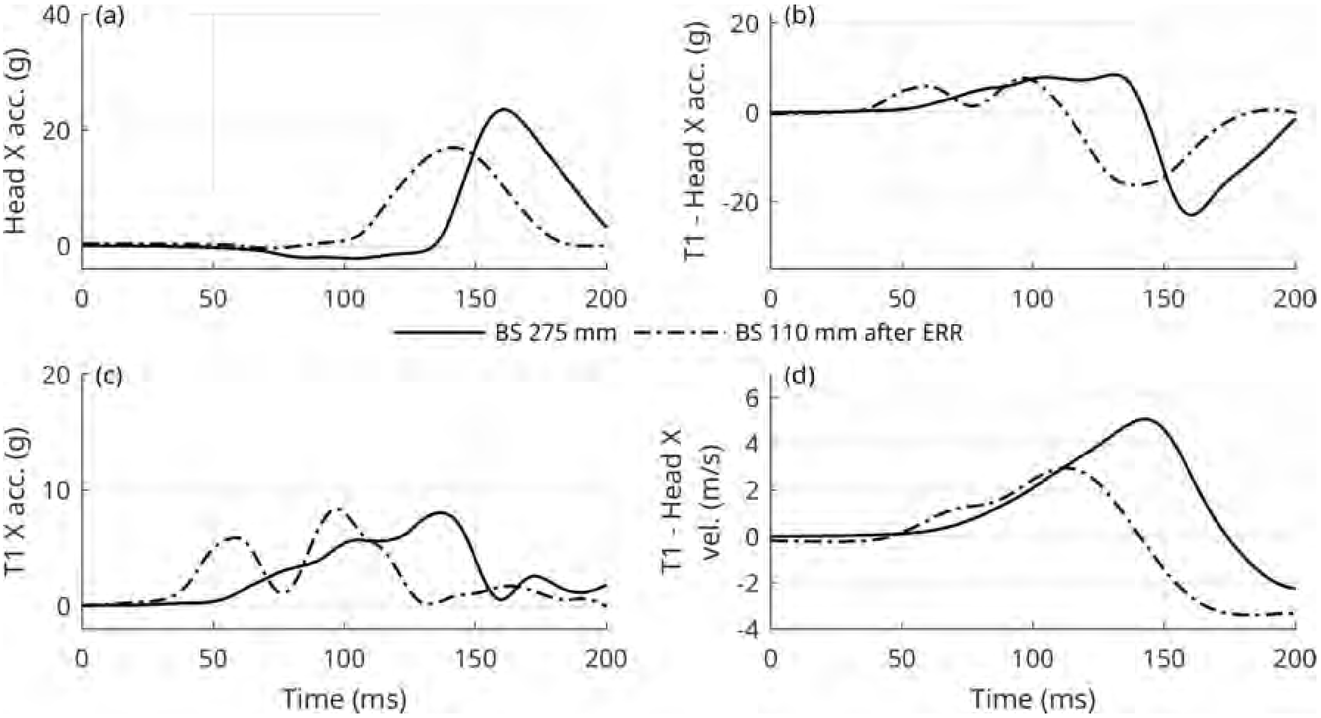

Fig. A7. Head X, T1 X, T1 − Head X acceleration (acc.) and T1 − Head X velocity in in rear-end impact tests with a forward leaning physical BioRID with an initial backset of 275 mm, with and without ERR activation prior to impact.

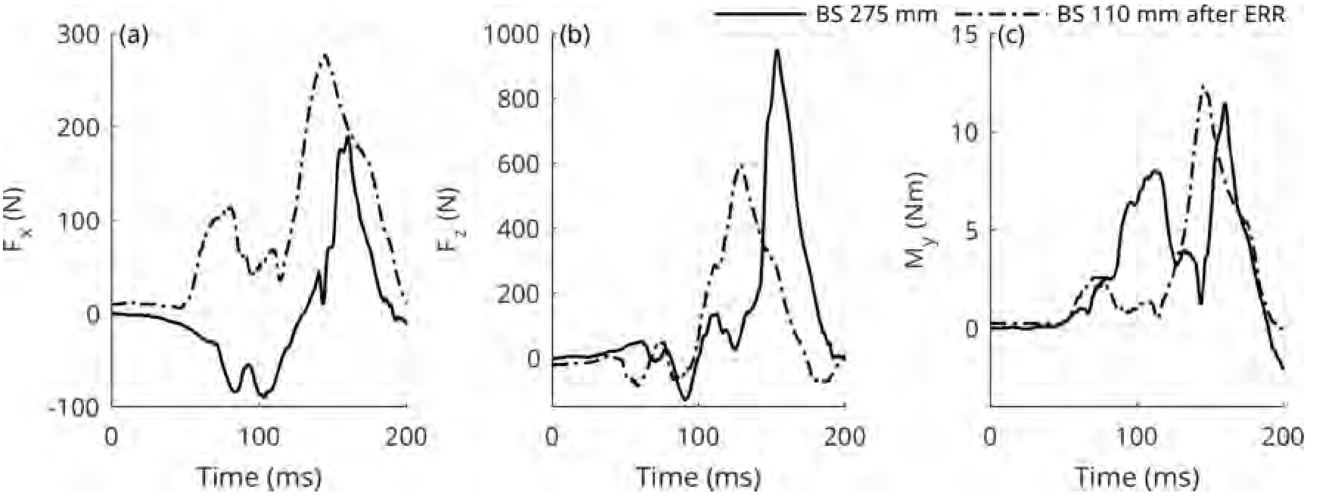

Fig. A8. Upper Neck $F_x$, $F_z$ and $M_y$ in rear-end impact tests with a forward leaning physical BioRID (initial backset of 275 mm), with and without ERR activation prior to impact.