Effectiveness of Active Restraint System Activated in Emergency Braking on Occupant's Whiplash Injury in Subsequent Rear-end Collision

Hang Qiu, Jing Fei, Yu Liu, Peifeng Wang,Cheng Lin, Puyuan Tan, Qing Zhou

Abstract In this study, we defined a rear-end collision occurring subsequent to an emergency braking as an integrated rear-end collision scenario. During the emergency braking stage, the vehicle occupant will be in forward out-of-position posture, which differs from the standard upright sitting posture tested in current rear-end collision safety assessment protocols (like Euro NCAP). A previous study has shown that an increased whiplash injury risk exists in this integrated rear-end collision scenario, and some vehicle manufacturers have designed an active pretensioning seatbelt or active headrest to resolve this issue. To investigate the effectiveness of these active restraint devices, BioRID II ATD was chosen to measure the whiplash injury metrics in an integrated rear-end collision sled test. The test results indicate that active headrest and active pretensioning seatbelt significantly reduce neck injuries. To evaluate the biofidelity of BioRID II ATD during the emergency braking stage, we recruited seven volunteers to conduct a 0.9 g emergency braking sled test, and recorded the lower neck's forward displacement during the braking. The results show that the BioRID II ATD had a larger forward displacement than the volunteers at the early stage of the emergency braking, but finally reached a stable forward displacement similar to the volunteers after a backward rebounding.

Keywords Rear-end collision, whiplash injury, out-of-position, active restraint system,volunteer test.

I. INTRODUCTION

Automatic Emergency Braking (AEB) systems are widely implemented in current vehicles, effectively reducing the frequency and severity of traffic accidents. However, these systems cannot prevent all potential accidents [1]. In situations where the collision is not successfully avoided, the forward displacement of the occupant caused by the emergency braking [2] may deteriorate the interaction between the occupant and the restraint system, increasing the injury severity [3]. In an accident study conducted by China Automotive Engineering Research Institute (CAERI), we identified a specific type of rear-end collision in which the leading vehicle initiates a sudden emergency braking, leaving insufficient time or space for the following vehicle to react, resulting in a collision (Fig. 1). A combined loading in both forward (braking) and rearward (rear-end collision) directions will be applied to the occupants inside the frontal vehicle. In this study, we defined this accident scenario as an integrated rear-end collision scenario. According to data from the Chinese National Automobile Accident In-depth Investigation System (NAIS), 77 of 631 rear-end collisions (12.2%) occurred while the frontal vehicles were in emergency braking stage.

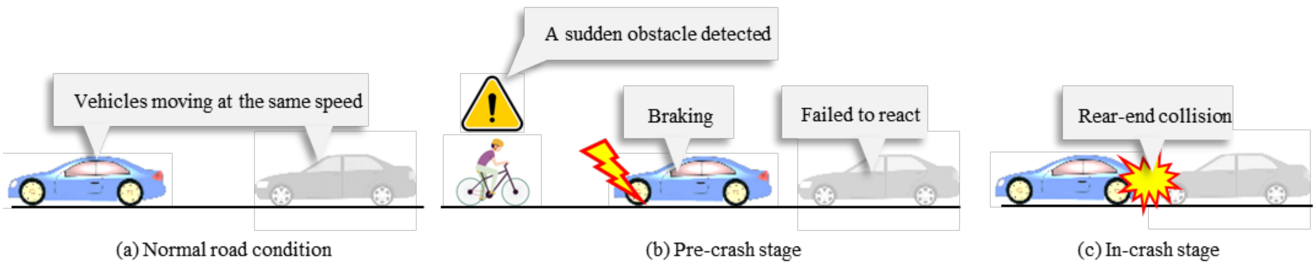

Fig. 1. Example of an integrated rear-end collision accident scenario.

Whiplash injury is a common neck injury for occupants in rear-end collisions. Although the bio-mechanism is not yet well understood, medical studies indicate that the rapid backward whiplash movement of the neck

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exacerbates the extension and tension of cervical vertebrae, increasing the injury risk of nerve fibers and soft tissues [4-5]. A previous study in 2015 suggested that the occupant forward out-of-position displacement caused by AEB would increase the whiplash injury risk in the subsequent rear-end collision, and recommended that using an active pretensioning seatbelt and active headrest could mitigate this risk [6].

To investigate the effectiveness of the active pretensioning seatbelt and the active headrest product, we designed a bi-directional loading sled test to represent the integrated rear-end collision accident. We compared the forward displacement of the BioRID II Anthropomorphic Test Device (ATD) with that of seven male volunteers during the emergency braking loading condition, confirming that the BioRID II ATD demonstrates preliminary biofidelity during the braking stage. This study explores the differences in whiplash injury outcomes of the BioRID II ATD between the integrated rear-end collision test and the traditional rear-end test, investigating the effectiveness of the active pretensioning seatbelt and the active headrest. The findings aim to provide insights into the occupant's neck protection under the integrated rear-end collision scenarios.

II. METHODS

Sled Test System and the Acceleration Pulse

The Seattle Safety ServoSled 3.1 MN sled test system was used in this study, where the acceleration pulse was controlled by both a hydraulic driving cylinder and a track braking device (Fig. 2). During the emergency braking stage, the hydraulic cylinder and the track braking device were activated simultaneously (Fig. 3). The track braking device provided braking force to counterbalance the excessive pushing force exerted by the hydraulic actuator, ensuring the sled system could move with an acceleration of approximately 1 g, to represent the emergency braking stage. In the rear-end collision stage, the hydraulic cylinder was deactivated, while the track braking device controlled the braking force to generate a standard moderate rear-end crash pulse as specified in current testing protocols, such as Euro NCAP 2024.

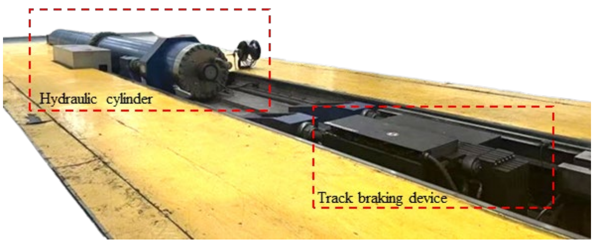

Fig. 2. Sled track and driving system.

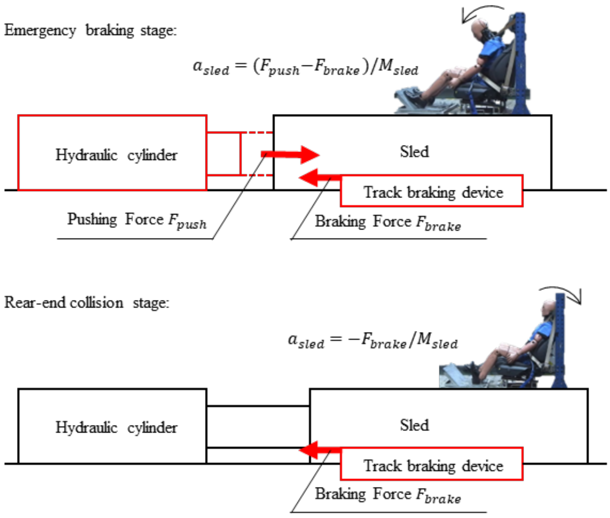

Fig. 3. Acceleration pulse control strategy.

When determining the target acceleration pulse for the emergency braking stage, we considered that, in real-world accidents, the more braking intensity of the leading vehicle, the more likely the following vehicle would fail to avoid the accident. Therefore, we selected the maximum AEB deceleration pulses from nine vehicles tested by CAERI in 2024. The deceleration pulses were simplified into trapezoidal shapes and the averaged maximum braking intensity (0.9 g) and the time required to reach this maximum intensity (300 ms) were calculated (Fig. 4). The focus was on the influence of the occupant forward out-of-position displacement compared to the standard rear-end collision test. A standard moderate crash pulse, as defined in Euro NCAP 2024 protocol, was chosen, which requires a velocity change between 14.8 km/h and 16.2 km/h. Therefore, in the integrated sled test, the sled must be accelerated to a speed over 16.2 km/h during the braking stage to ensure sufficient kinetic energy for the subsequent rear-end collision stage. The final target acceleration pulse for the integrated rear-end collision test is shown in Fig. 5, with a target 17.5 km/h velocity change at 700 ms.

Evaluation of BioRID II's Biofidelity in the Emergency Braking Stage

To investigate whether the BioRID II ATD can exhibit realistic kinematic response of the occupant during the emergency braking stage, we recruited seven healthy adult male volunteers to conduct emergency braking sled tests. A displacement sensor fixed near the headrest (as shown the Appendix, in Fig. A1(a)) was used to measure the forward displacement of the T1/C7 vertebra (lower neck) during the emergency braking stage. The results were then compared to the test data measured from the BioRID II ATD. More details of the experiment can be found in the Appendix.

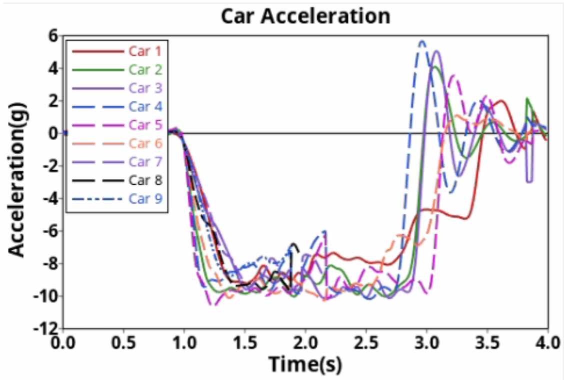

Fig. 4. Maximum AEB deceleration pulses.

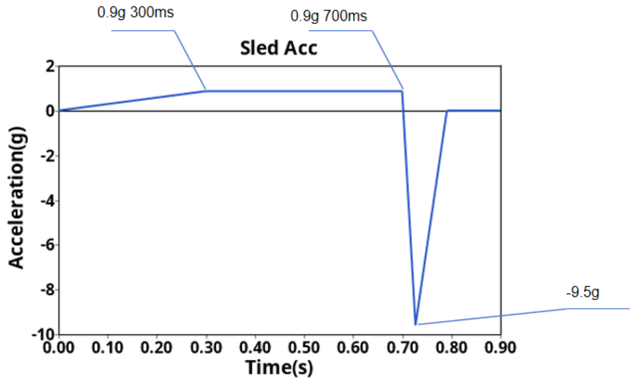

Fig. 5. Target sled test acceleration pulse.

Effectiveness of Active Restraint System in the Integrated Rear-end Collision Scenario

To investigate the effectiveness of the active pretensioning seatbelt and the active headrest supplied by a vehicle manufacturer, a vehicle seat was installed onto the sled, with adjustments made to the seat height, seatback angle, and the positions of the D-ring, retractor, and anchor points according to the configuration in the real vehicle. The tested seat was equipped with an active pretensioning seatbelt that could be activated together with the initiation of the emergency braking. The active pretensioner would continuously pull seatbelt webbing into the retractor with a 200 N pretensioning force until the force was insufficient to retract the seatbelt. Meanwhile, the active headrest of the tested seat could move forward 50 mm distance under the control of an electric motor during the emergency braking stage, bringing the headrest closer to the occupant's head. In this study, we conducted three integrated rear-end collision sled tests. Additionally, a traditional rear-end collision test was also conducted as the baseline. The test matrix is shown in Table I. In each test, the time history curves of the whiplash injury metrics (including neck shear force, neck tensile force, Neck Injury Criteria (NIC) and Nkm) measured from the BioRID II ATD during the rear-end collision stage were recorded.

TABLE I
EXPERIMENT MATRIX

Test Number	Test Scenario	Active Pretensioning Seatbelt	Active Headrest
Test 1		Deactivated	Deactivated
Test 2	Integrated rear-end collision	Activated	Deactivated
Test 3		Deactivated	Activated
Test 4 (Baseline)	Traditional rear-end collision	Deactivated	Deactivated

III. RESULTS

Evaluation of BioRID II's Biofidelity in the Emergency Braking Stage

Figure 6 shows the distribution of the forward displacement for the lower neck markers on the BioRID II ATD and the seven volunteers during the emergency braking stage. It can be observed that the forward displacement of the volunteers increases in the first 500 ms until reaching the maximum value, followed by a slight rebound, and eventually stabilises at around 700 ms. Using the displacement at 700 ms as a reference, the average forward displacement of the seven volunteers was 146(±66.5) mm for the neck. In contrast, the BioRID II ATD reached its maximum forward displacement earlier, at around 450–500 ms, followed by a larger rebound, and approached its final position after 700 ms. The peak forward displacement for the BioRID II ATD was 210 mm for the neck, while the reference final displacement was 146 mm at 700 ms.

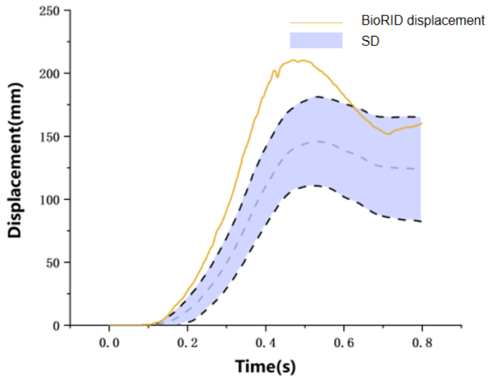

Fig. 6. Forward displacement of lower neck.

Effectiveness of Active Restraint System in the Integrated Rear-end Collision Scenario

When evaluating the severity of the neck whiplash injury, it is generally believed that the backward whiplash motion of the neck and the corresponding loads during this movement are the primary causation of the whiplash injury. When reading the injury outcomes of the ATD, only the positive peak values of each injury metrics were recorded and evaluated, while the negative peak values caused by neck flexion during the final rebounding stage at the later time of the rear-end collision were not considered. Table II shows the positive peak values of the neck shear force, neck tensile force, NIC, and Nkm recorded in the four tests (listed in Table I), along with the performance limitations required by the current Euro NCAP and C-IASI whiplash protocols. Time history curves of the whiplash injury metrics can be found in the Appendix.

TABLE II
WHIPLASH INJURY OUTCOMES

Test Number	Neck shear force (N)	Neck tensile force (N)	NIC	Nkm
Test 1	154	982	54	0.87
Test 2	87	783	38	0.36
Test 3	11	1123	39	0.37
Test 4	0	484	19	0.26
Euro NCAP lower limit	290	750	24	0.69
C-IASI lower limit	154	821	23	Not evaluated

IV. DISCUSSION

Evaluation of BioRID II's Biofidelity in the Emergency Braking Stage

The BioRID II ATD exhibited an earlier and larger forward displacement at the beginning of the emergency braking stage. This may be attributed to the fact that the BioRID II ATD was not designed and validated for frontal loading conditions, leading to the omission of the rib-cage structure. The thoracic cavity of the BioRID II ATD is primarily filled with elastic rubber materials. During the first 450 ms of emergency braking, the rubber within the thoracic cavity stored a certain amount of elastic potential energy, which subsequently released as the thoracic spine rebounded later. The forward displacement of the ATD at the end of the emergency braking fell within the volunteers' distribution range. Therefore, we believed that the BioRID II ATD was capable of representing the occupant's forward displacement during the braking scenario.

It should be noted that the forward displacements of the volunteers measured in this study are generally greater than the results reported by [7] or [8]. This discrepancy might be because, in this study, to prevent the volunteers from impacting the frontal windshield, we adjusted the vehicle seat to the lowest and furthest position from the instrument panel. Under this configuration, the restraint effectiveness of the three-point seatbelt was weaker. Also, the volunteers' feet were away from the frontal foot pedals, making it difficult for their legs to provide support. As a result, the forward displacements measured in this study might be larger.

Effectiveness of Active Restraint System in the Integrated Rear-end Collision Scenario

In Test 4, the tested seat achieved a GOOD rating according to the Euro NCAP and C-IASI protocols. However, in the integrated rear-end collision scenario (Test 1), the whiplash injury metrics increased significantly. This could be attributed to the forward out-of-position of the occupant during the emergency braking, which resulted in a larger acceleration distance for the torso and head before impacting the seatback and headrest. Furthermore, the forward flexion of the neck before the rear-end collision exacerbated the whiplash motion during the collision stage. After the active pretensioning seatbelt activated in Test 2, the out-of-position displacement of the ATD in the braking stage was reduced, which decreased the impact intensity between the ATD and the seat during the rear-end collision stage, thereby decreasing the whiplash injury loads.

After the active headrest activated in Test 3, the forward out-of-position displacement of the ATD torso was not controlled, but the headrest moved closer to the head. At the beginning of the rear-end collision, the ATD horizontally translated backwards to the seatback. After the ATD's back fully contacted with the seatback, the ATD's neck started to swing backward and ultimately impacted with the headrest. During this backward movement process, the neck shear force changed from negative value to positive value, and the neck bending condition changed from flexion to extension. The active headrest could reduce the distance between the head and the headrest and decrease the backward whiplash rotation angle of the neck. Therefore, the extension bending degree and backward shearing force, which are considered to be the cause of whiplash injury, decreased in this test condition.

Both active restraint systems demonstrated a positive effect in mitigating whiplash injury in the integrated rear-end collision scenario. However, the whiplash injury loading metrics of the ATD remained larger than the whiplash protection requirements in current testing protocols. It is important to note that whiplash injury is a minor injury, and exceeding the limits established in current protocols does not necessarily indicate any severe injuries. In the future safety evaluations, both whiplash evaluation metrics and scoring thresholds should be updated based on the performance of actual vehicle seats and the application of the active restraint systems.

V. CONCLUSION

The BioRID II ATD exhibits the limitation of excessive peak displacement during the emergency braking stage. However, as the braking time extends, the ATD can primarily represent the displacement behaviour of the volunteers after the backward rebounding, demonstrating a basic capability to perform the integrated rear-end collision test we defined in this study. In the integrated rear-end collision test scenario, the neck whiplash injury parameters of current automotive seats show a significant increase. The active pretensioning seatbelt can reduce the whiplash injury load by limiting torso forward bending, while the active headrest can mitigate the load by reducing the amplitude of head movement. The combination effect of the two systems should be considered to achieve better protection results. And the requirements for traditional rear-end collisions may not be suitable for the integrated rear-end collision scenario and should be updated in the future.

VI. ACKNOWLEDGEMENTS

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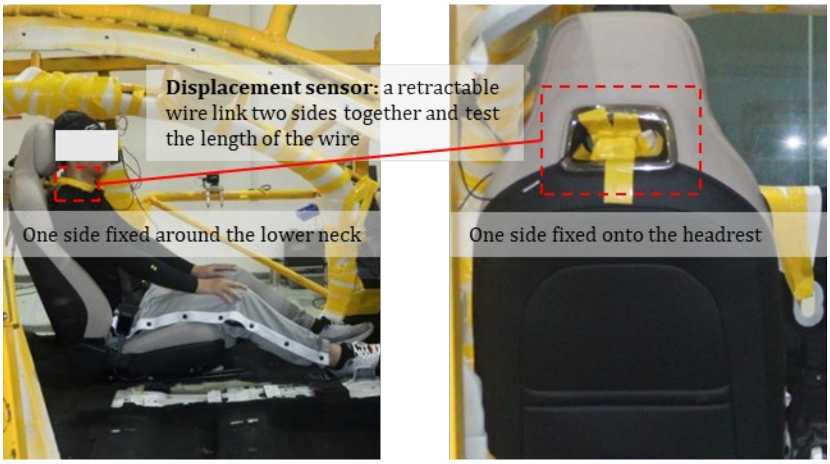
VIII. APPENDIX

TABLE AI
VOLUNTEER INFORMATION (INCLUDING HEIGHT, WEIGHT, AND BMI)

VOLUNTEER NO.	HEIGHT (CM)	WEIGHT (KG)	BMI
1	175	65	21.2
2	174	75	24.8
3	180	65	20.1
4	175	63	20.6
5	177	67.5	21.5
6	176	74	23.9
7	173	70	23.4



(a) (b)

Fig. A1. Setup of the volunteer test: (a) sitting postures of the volunteer; (b) displacement sensor fixed onto the headrest and lower neck.

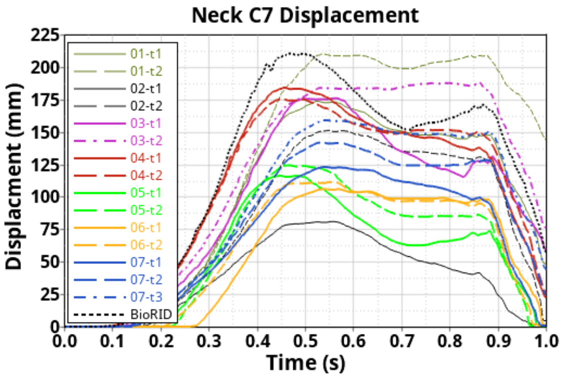


Fig. A2. Lower neck forward displacement tested in the volunteer tests and a BioRID II ATD test.

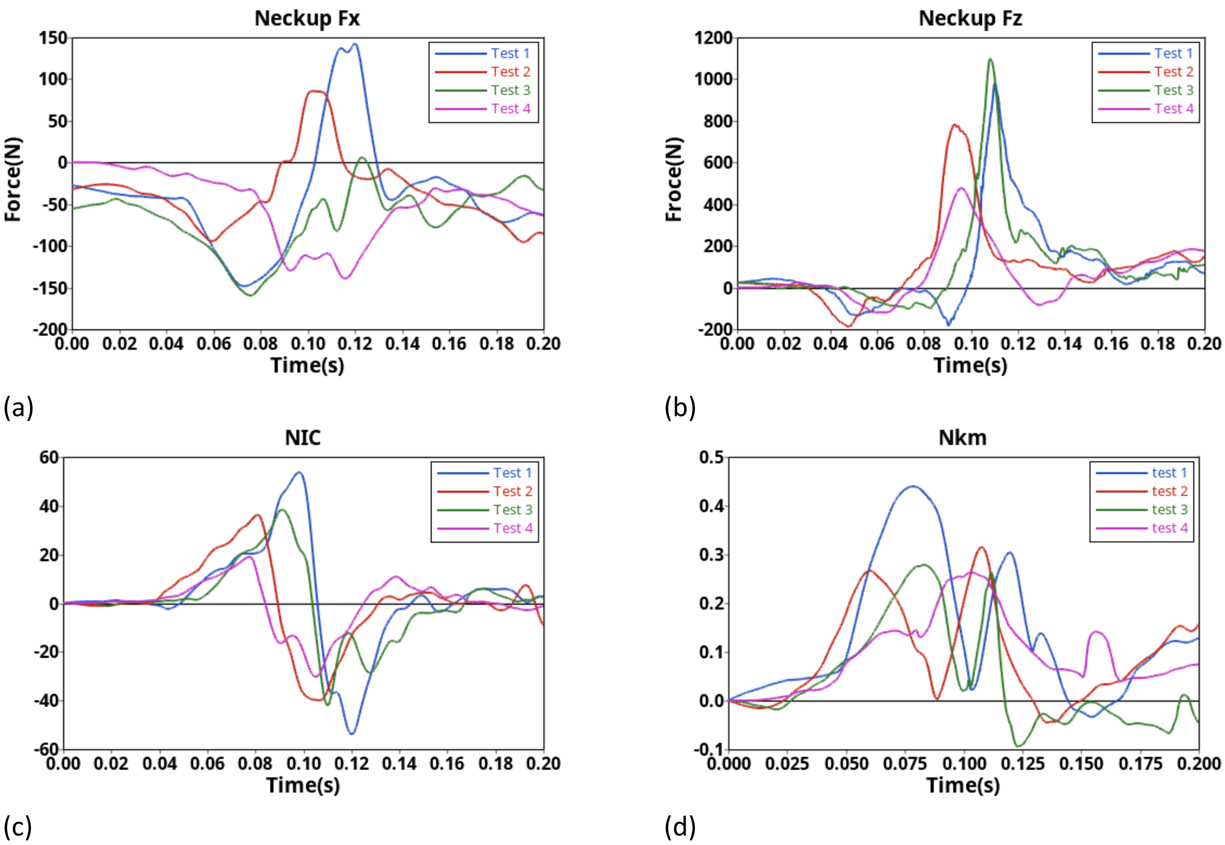


Fig A3. Time history curves of the whiplash injury metrics tested in Test 1 to Test 4: (a) Neck shearing force; (b) Neck tension force; (c) NIC; (d) Nkm

(Time = 0 represents the initiation of rear-end collision)