Correct Use of a Conventional Lap-and-Shoulder Seatbelt Is Safest for Pregnant Rear-Seat Passengers : Proposal for Additional Safety Measures

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Article

Correct Use of a Conventional Lap-and-Shoulder Seatbelt Is Safest for Pregnant Rear-Seat Passengers: Proposal for Additional Safety Measures

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Abstract: The objectives of this study were to assess the safety of various methods of seatbelt use and propose safety improvements to the lap-and-shoulder seatbelt for pregnant rear-seat passengers. The Maternal Anthropometric Measurement Apparatus dummy, version 2B, was used. Sled tests were performed to simulate frontal impact at a speed of 48 km/h in the right rear seat. Kinematics of the dummy were examined using high-speed video imaging, and time courses of the seatbelt loads and displacement and acceleration of the chest and pelvis were measured during impact. The kinematic parameters were compared under the following conditions: conventional lap-and-shoulder seatbelt used correctly, lap belt crossed over left and right femurs, and lap belt attached to both thighs using an extra restraint device. Then, by applying pretensioner and/or force limiter systems, the safest condition was investigated. Correct conventional seatbelt use was the most effective restraint method. When both pretensioner and force limiter were applied, the kinematic parameters were smallest, and the best restraint was achieved. The safety of rear-seat travel can be improved by using both pretensioner and force limiter systems, which would reduce the risk of chest and abdominal injuries to pregnant passengers and prevent negative fetal outcomes.

Keywords: safety; motor vehicle collision; rear seat; pregnancy; fetus; seatbelt

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1. Introduction

Decrease of casualties of motor vehicle collisions (MVCs) is a high priority worldwide. The World Health Organization reported in 2018 that approximately 1.35 million deaths each year result from MVCs [1]. To reduce fatalities in MVCs, injury mechanisms and effective safety interventions must be identified. Pregnant women are sometimes involved in MVCs, which cause maternal injuries and potentially lead to negative fetal outcomes. Vladutiu et al. reported that 2.9% of pregnant women were involved in MVCs in North Carolina between 2001 and 2008, and the stillbirth rate for such pregnancies was 0.56%, which is significantly higher than that recorded in the absence of MVCs [2]. Connolly et al. reported that 6–7% of pregnant women suffer from some form of traumatic injury during pregnancy, with approximately two thirds of these being related to MVCs [3]. For women who gave birth between 1 July 2000 and 30 June 2007 in New South Wales, Australia, MVCs during pregnancy resulted in 3.5 maternal fatalities per 100,000 pregnancies, as well as a fetus/neonate mortality rate of least 5.6 per 100,000 pregnancies [4]. Therefore, as a considerable number of pregnant women or the fetus were lost due to MVCs, mechanisms of injuries of pregnant women vehicle passengers should be clarified for promoting prevention measures.

Wearing a lap-and-shoulder seatbelt is effective for decreasing severity and fatality of MVC-related injuries. According to the studies based on real-world MVCs, pregnant drivers who wear a seatbelt have less severe maternal injuries and lower fetal fatality rates, compared with those who do not [5,6]. The American College of Obstetricians and Gynecologists, therefore, recommend a correct seatbelt use for preventing both pregnant women and fetus injuries [7]. Some biomechanical studies using a pregnant dummy confirmed that lap-and-shoulder seatbelts could improve the safety of pregnant women and the fetus when suffering from MVCs [8,9].

In Japan, pregnant women prefer to sit in the rear seats during pregnancy [10]. Worldwide, although pregnancy has no effect on the preference for front or rear seats [11,12], the seatbelt use rate of pregnant women in rear seats is significantly lower than that in front seats [13]. Therefore, correct rear seatbelt use should be promoted. The respective rates of seatbelt use by rear-seat passengers, drivers, and front-seat passengers are 42.9%, 99.1%, and 96.7% in Japan and 77.5%, 90.9%, and 89.8% in the United States [14,15]. Among pregnant women who sit in the rear seat, less than 20% always use a seatbelt and 29% sometimes use one [16]. Other studies reported that 22.5% of pregnant women who improperly used a seatbelt passed the lap belt over the thighs [17]. Furthermore, extra restraint devices that have recently become available pass the lap belt across both thighs and anchor it between them [18]. These appeal to pregnant women, who are hesitant to pass the lap belt around the abdomen to avoid discomfort. Despite low rates and improper methods of seatbelt use during pregnancy, the effect of these situations on pregnant passenger safety has not been assessed scientifically.

Forensic scientists are required to determine the causal relationship between MVCs and fetal deaths, following MVC-induced injuries to pregnant women. Negative fetal outcomes are often observed when restrained pregnant women are involved in even minor vehicle collisions [19]. In addition, the psychological stress caused by MVCs sometimes has a significant influence on the mental health of pregnant women, and this might have a negative effect on their fetus. Therefore, the kinematics of restrained motor vehicle passengers must be understood. Although biomechanical insight for correctly restrained vehicle passengers has been obtained, the kinematics of vehicle passengers who improperly use conventional seatbelts remain to be understood. Detailed knowledge regarding the injury mechanisms of incorrectly restrained pregnant women is required to inform the decisions of forensic pathologists and justice officials. Hence, our study aimed to use kinematics and applied physiology to assess various methods of seatbelt use and propose safety improvements to the lap-and-shoulder seatbelt used by pregnant rear-seat passengers.

2. Materials and Methods

2.1. Research Protocol

2.1.1. Safety Evaluation of Various Methods of Seatbelt Use

To evaluate the hazards of passing the lap belt across the thighs, dummy kinematics and biomechanical parameters were compared among various methods of seatbelt use. According to a previous report regarding incorrect seatbelt use, many pregnant women pass the lap belt over the thighs and insert towels or other objects between the lap belt and body [17] to avoid contact between the lap belt and the abdomen. Therefore, to simulate these conditions, one sled test was performed in each of the following conditions: (A) a correctly used seatbelt, with lap-and-shoulder belts positioned to avoid the protruding abdomen (Figure 1); (B) the same shoulder belt position as in test A, but with a sponge inserted between the lower abdomen and the lap belt, so that the latter passes across the left and right thighs (Figure 2); (C) the same shoulder belt position as in test A, but using an additional BeSafe Gravid (HTS BeSafe AS, Kroeden, Norway) device [20] to pass the lap belt across both thighs and anchor it between them (Figure 3).

Figure 1. Version 2B of the Maternal Anthropometric Measurement Apparatus (MAMA-2B), restrained in the test setup using a correctly positioned conventional seatbelt.

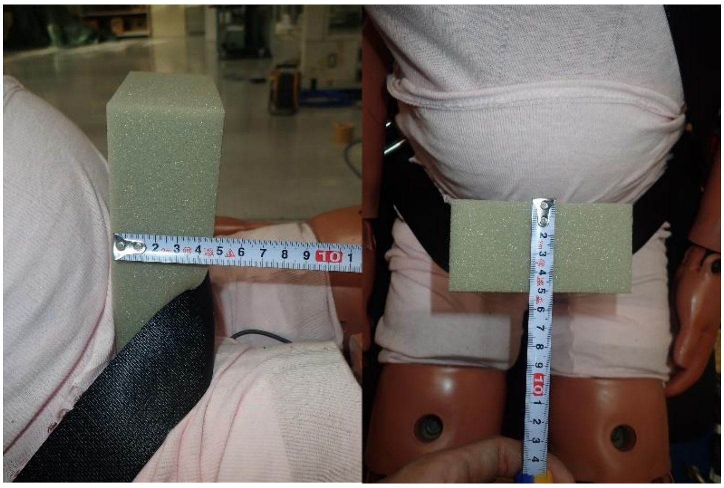

Figure 2. Test setup of the MAMA-2B dummy with a sponge inserted between the lower abdomen and lap belt, so that the lap belt passes across the left and right thighs.

2.1.2. Application of Pretensioner and Force Limiter Systems

To propose an improved restraint system for rear-seat passengers, we applied the pretensioner and force limiter that are usually installed in both front seats [21]. The pretensioner, which retracts the safety belt almost instantly in a crash to prevent excess slack, secures the passengers to the vehicle, while decelerating early during a crash. The force limiter lessens the risk of upper body injuries by releasing the shoulder belt at forces above a predefined threshold. We set the threshold of the force limiter to 3.0 kN, consistent with the current value used in passenger vehicles. In addition to tests A–C, we further compared the kinematics and biomechanical parameters of a dummy restrained by a correctly fitted seatbelt equipped with (D) neither pretensioner nor force limiter, (E) a pretensioner only, (F) a force limiter only, and (G) both a pretensioner and force limiter.

Because dynamic changes to the seatbelt system occurred under these conditions, sled tests were performed three times for each.

Figure 3. Test setup of the MAMA-2B dummy with the lap belt passed across both thighs and anchored between them using an extra restraint device.

2.2. Test Setup

The test dummy was the Maternal Anthropometric Measurement Apparatus, version 2B (MAMA-2B), developed by the University of Michigan Transportation Research Institute and First Technology Safety Systems [22,23]. This dummy, representing pregnant women at 30 weeks of gestation, with a height of 153 cm, modified by small size of female crash test dummy (5% tile size of Hybrid III dummy), was confirmed to use for official crash test for accident research [24].

The interior buck was based on the actual vehicle body of compact car. The seat represented the right rear position of a typical compact car, with a seat-back angle of 20°. The HyGe sled test facility was used for sled tests, according to the published protocols [25]. All test conditions used full frontal impact at a target velocity of 48 km/h. Acceleration pulses (crash pulses) were applied as previously reported [23].

2.3. Measurements

The overall kinematics of the dummy, including the trajectory during impact, were measured using a high-speed (1000 fps) video recorder. We measured dummy responses, such as the displacements and accelerations of the head, chest, and pelvis along the horizon (X), vertical (Y), and depth (Z) axes (Figure 4). The resultant accelerations of the head, chest, and pelvis were calculated from the square root of the sum of the squares of their respective x, y, and z accelerations. In addition, the moment around the Y-axis of the neck, corresponding to extension or flexion of the neck, was measured. The data were digitized with a high-speed data acquisition system (20 kHz sampling rate) and then filtered with a channel frequency class 180 filter (chest and pelvis data) or a class 1000 filter (head and neck data) [26]. Deflections of the chest were measured using the so-called infrared telescoping rod for assessment of chest compression (IR-TRACC) system, which was mounted inside both side of front chest corresponding to second ribs of the dummy. During impact, we also measured the loads on the shoulder and lap sections of the seatbelt, hereafter referred to as the shoulder and lap loads, respectively.

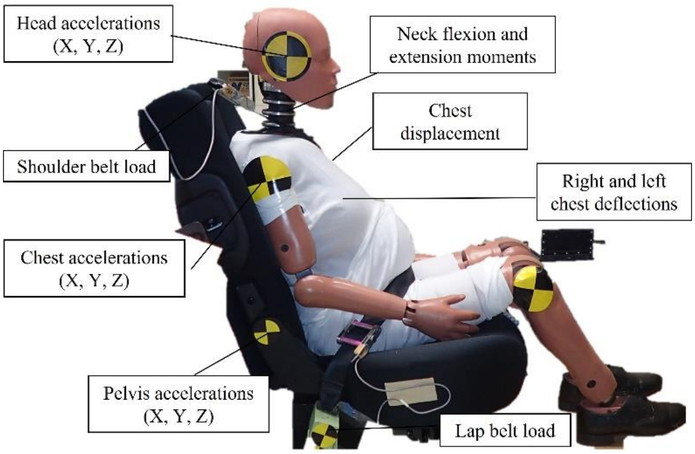

Figure 4. Types and locations of measurements made using the MAMA-2B dummy during sled tests.

3. Results

3.1. Safety Evaluation of Various Methods of Seatbelt Use

3.1.1. Dummy Kinematics

After the onset of collision, the dummy moved forward, and the peak head excursions in each test were observed at 102 to 106 ms after impact (Figure 5).

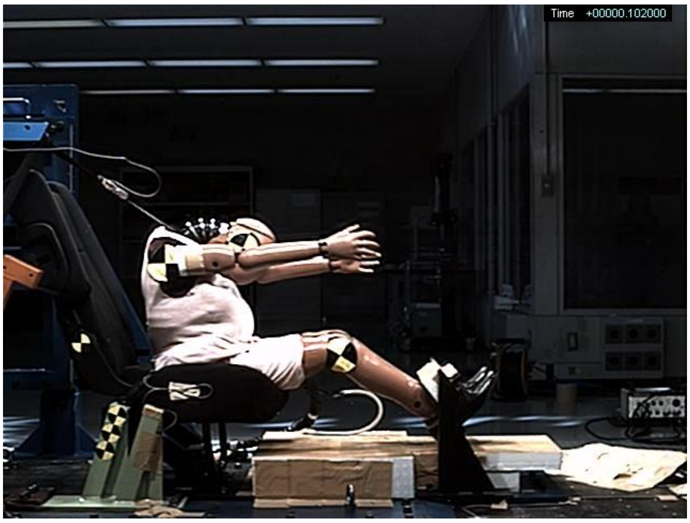

Figure 5. Representative image of the dummy 102 ms after impact, showing the point of peak head excursion (test A).

Figure 6 shows the time courses of the chest displacements along the horizon axis during frontal MVC tests A–C. In test A, the maximum chest displacement of 230.9 mm from its initial position was reached 69 ms after impact. In test B, the maximum chest displacement of 260.0 mm was reached after 71 ms; in test C, the maximum of 278.8 mm was reached after 71 ms.

3.1.2. Biomechanical Values

Maximum values of each parameter were shown in Table 1. In test A, the maximum resultant accelerations of the head (308.8 m/s^2), chest (639.4 m/s^2), and pelvis (323.0 m/s^2), as well as the neck extension moment (33.2 Nm) and maximum loads on the lap (9.3 kN) and shoulder (11.0 kN) belts, were the smallest among tests A–C, with the corresponding parameters being largest in test B and, in most cases, highest in test C. The highest neck flexion moment was obtained in test A and the lowest in test B. The largest chest deflection was obtained in test C, with the lowest in test B.

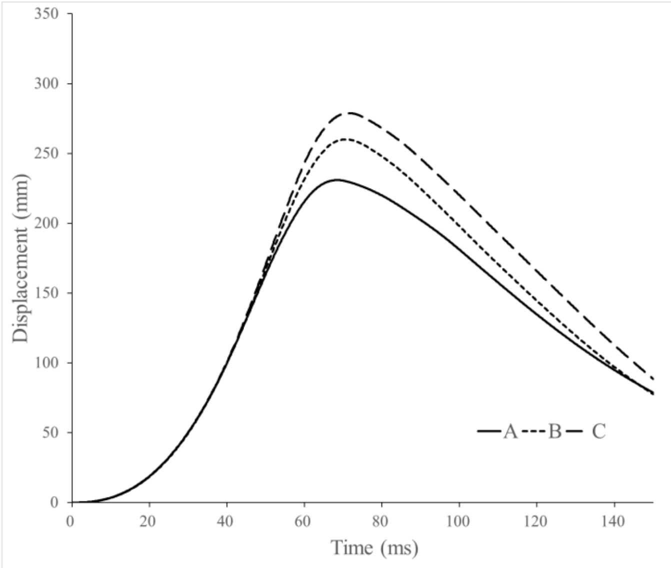

Figure 6. Time courses of the chest displacement using the restraint methods shown in Figures 1–3.

Table 1. Maximum head, chest, and pelvis accelerations, neck flexion and extension moments, chest deflections, and seatbelt loads using the seatbelt arrangements shown in Figure 1 (test A), Figure 2 (test B), and Figure 3 (test C).

Parameter		Test A	Test B	Test C
Head	Resultant accel. (m/s^2)	308.8	340.0	371.3
	Time (ms)	102	67	69
Neck	Flexion moment (Nm)	101.2	75.1	84.5
	Time (ms)	98	98	102
	Extension moment (Nm)	33.2	35.1	43.3
	Time (ms)	64	67	67
Chest	Resultant accel. (m/s^2)	639.4	825.8	773.9
	Time (ms)	64	67	62
	Deflection right (mm)	8.4	7.8	10.0
	Time (ms)	104	103	104
	Deflection left (mm)	28.5	26.1	28.5
	Time (ms)	77	79	81
Pelvis	Resultant accel. (m/s^2)	323.0	388.1	396.8
	Time (ms)	66	68	68
Seatbelt loads	Lap load (kN)	11.0	11.8	11.9
	Time (ms)	61	65	66
	Shoulder load (kN)	9.3	9.9	10.6
	Time (ms)	64	66	68

3.2. Application of Pretensioner and Force Limiter Systems

3.2.1. Dummy Kinematics

After the onset of collision, neck flexion was observed during the forward movement of the dummy. The average time of peak head excursion after the onset of collision varied, depending on the test condition: 102 ms (test D), 103 ms (test E), 123 ms (test F), and 122 ms (test G).

Figure 7 shows the time courses of the average chest displacement along the horizon axis during the frontal MVC tests D–G. In test D, the maximum chest displacement of 234.1 mm from its initial position was reached 69 ms after impact. In test E, the maximum chest displacement reached 195.4 mm after 74 ms. In test F, the maximum displacement was 316.5 mm after 93 ms. In test G, the maximum was 257.1 mm after 93 ms.

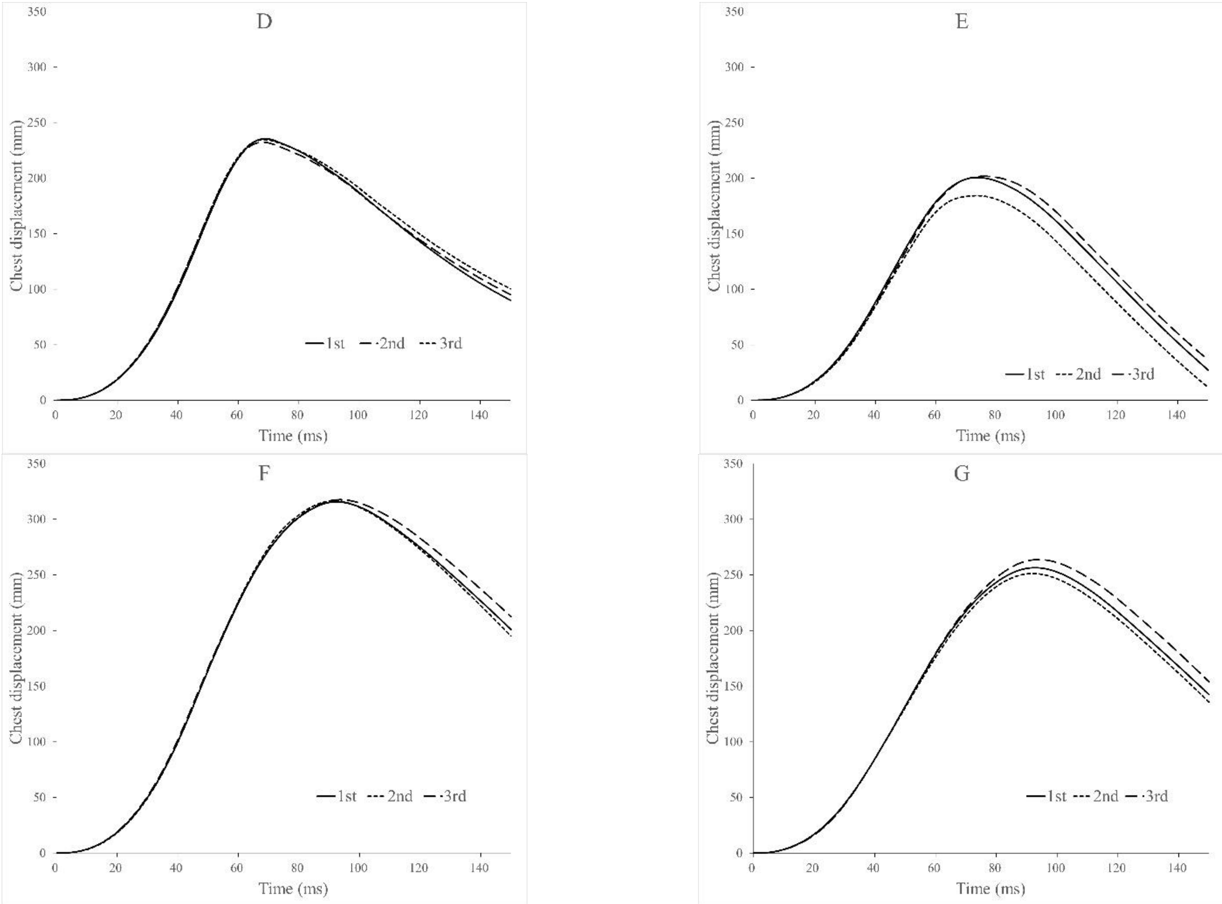

Figure 7. Time courses of the chest displacement, using a correctly fitted seatbelt, optionally equipped with a pretensioner and/or force limiter.

3.2.2. Biomechanical Values

The average maximum value of each parameter is shown in Table 2. In test D, the maximum resultant accelerations of the head (312.0 m/s^2), chest (666.2 m/s^2), and pelvis (320.4 m/s^2), as well as the neck extension moment (38.2 Nm) and maximum loads of the lap (11.1 kN) and shoulder (9.2 kN) belts, were the highest among tests D–G. In test E, the maximum resultant accelerations of the head, chest, and pelvis, as well as the neck extension moment and maximum belt load, were lower than those in test D. In test F, the maximum resultant accelerations of the head and chest, neck flexion, extension moments, and maximum lap belt load were lower than those in test D, and the maximum shoulder belt load (3.8 kN) was the lowest among tests D–G. In test G, all parameter values were lower than those in test D, and the maximum values of the head and chest resultant accelerations, neck flexion, extension moments, chest deflections, and lap seatbelt load were the lowest among tests D–G. The largest and smallest chest deflections were obtained in tests D and G, respectively.

Table 2. Average maximum head, chest, and pelvis accelerations, as well as neck flexion, extension moments, chest deflections, and seatbelt loads, using a correctly positioned conventional seatbelt (Figure 1), equipped with neither pretensioner nor force limiter (Test D), a pretensioner only (Test E), a force limiter only (Test F), or both a pretensioner and force limiter (Test G).

Parameter		Test D (Conventional Seatbelt)	Test E (PT)	Test F (FL)	Test G (PT + FL)
Head	Resultant accel. (m/s^2)	312.0	305.7	273.1	259.3
	Time (ms)	76	91	91	96
Neck	Flexion moment (Nm)	73.1	83.5	68.2	62.8
	Time (ms)	98	99	118	117
	Extension moment (Nm)	38.2	21.6	20.6	16.1
	Time (ms)	62	64	76	79
Chest	Resultant accel. (m/s^2)	666.2	470.4	357.2	284.4
	Time (ms)	64	60	71	66
	Deflection right (mm)	8.5	9.0	6.9	6.8
	Time (ms)	106	107	125	104
	Deflection left (mm)	26.9	25.6	21.9	19.8
	Time (ms)	69	81	64	91
Pelvis	Resultant accel. (m/s^2)	320.4	221.6	304.4	221.8
	Time (ms)	63	62	69	68
Seatbelt loads	Lap load (kN)	11.1	8.1	9.2	7.2
	Time (ms)	61	58	61	59
	Shoulder load (kN)	9.2	7.4	3.8	3.8
	Time (ms)	64	68	75	57

PT: pretensioner, FL: force limiter, accel: acceleration.

4. Discussion

By analyzing the kinematics and biomechanical parameters of a pregnant dummy, we examined the safety of a correctly used conventional lap-and-shoulder seatbelt for pregnant rear-seat passengers and further analyzed the safety of a conventional seatbelt equipped with pretensioner and force limiter systems. Because we used a pregnant woman dummy with a similar stature to an average Japanese pregnant woman [9], this reconstruction of a motor vehicle collision involving a pregnant woman sitting in the rear seat had enough reliability. In this context, one previous study performed sled tests using a similar dummy to examine the mechanism of neck injuries, due to shoulder belt compression [27]. However, because neither the interaction between the lap belt and abdomen nor the seatbelt loads were examined, to our knowledge, our study is the first to examine the kinematics of the entire body and its related parameters under the seatbelt conditions used by pregnant passengers.

Seatbelt methods that pass the lap belt across the left and right thighs or use the extra restraint device resulted in greater displacements and resultant accelerations of the head, chest, and pelvis than the correct use of the conventional seatbelt. On the basis of these results, we concluded that the correctly used conventional lap-and-shoulder seatbelt provided enough safety. Previous reports suggested that 12.7–27.5% of pregnant women wear seatbelts incorrectly, due to the misunderstandings regarding the correct way to use them [17,28]. Therefore, healthcare professionals must educate pregnant women about the correct use of conventional rear-seat safety belts, based on current scientific evidence.

To improve the safety of pregnant rear-seat passengers, it is important to provide better restraint and reduce the applied external forces. Previously, rear-seat passengers were considered to be safer than front seat passengers. However, the widespread installation of seatbelt safety systems with a pretensioner and force limiter has dramatically improved the safety of front seats. In contrast, the safety of rear seats remains minimally improved [29,30]. Jermakian et al. reported that rear-seat passengers suffered more serious chest injuries than drivers or front seat passengers in MVCs, owing to the lack of a pretensioner and force limiter in the rear seat [31]. Jingwen et al. reported that a pretensioner and force limiter improved the safety of rear seats [32]. We, therefore, evaluated the efficiency of pretensioner and force limiter systems for pregnant passengers. A previous study evaluated these systems for the pregnant drivers using the MAMA-2B dummy [33] and concluded that activating the pretensioners and force limiters in a rear-end collision could improve safety. However, to the best of our knowledge, our study is the first to examine the use of pretensioners and force limiters during frontal collisions involving pregnant rear-seat passengers.

Using a pretensioner, which quickly retracts some of the seatbelt webbing during a collision, the maximum chest displacement, maximum resultant acceleration of the head, chest, and pelvis, neck extension, and seatbelt loads were smaller than those resulting from conventional seatbelt use. These results indicate that the pretensioner improves restraint and, thus, the safety of the passenger. However, the chest deflections and neck flexion were slightly higher than those resulting from conventional seatbelt use because of the early restraint of the pretensioner. Using a force limiter, which releases the webbing gradually, while maintaining a constant force to restrict the force on the chest, the chest displacement was larger than that resulting from conventional seatbelt use.

When both the pretensioner and force limiter were applied, the magnitudes of almost all measured parameters (except for the chest displacement) were smaller than those resulting from conventional seatbelt use. Furthermore, the combined use of the pretensioner and force limiter produced a resultant head and chest acceleration, neck flexion, and extension, chest deflections, and seatbelt loads lower than those resulting from use of one or neither of them. According to Mertz et al., both the skull fracture and neck injury risks with an abbreviated injury scale (AIS) score > 3 are less than 1% [34]. Based on the findings of Kleinberger et al., the chest resultant acceleration of 284.4 m/s^2 obtained in the present study presents only a 10.9% risk of injuries, with an AIS > 3 [34,35]. Mertz et al. reported that a chest injury with an AIS $\geq$ 3 did not occur when the shoulder belt load was less than 4.0 kN [36]. Additionally, according to vehicle safety regulations, the chest deflection of 19.8 mm obtained in the present study presents only a 7.2% risk of injuries with an AIS > 3 [37]. Therefore, we conclude that the risk of chest injury to pregnant rear-seat passengers might be reduced by using pretensioner and force limiter systems. Furthermore, as previously suggested, because the uterine fundus extends into the upper abdomen in late-term pregnancy, reductions of both the shoulder belt load and chest deflection would minimize the direct forces on the uterus [38]. When both pretensioner and force limiter were applied, the average lap belt load was 7.2 kN. On the basis of swine experiments, Millar reported that abdominal injuries with AIS $\geq$ 3 occurred in 50% of cases, when the maximum lap belt load was 3.96 kN [39]. Therefore, we concluded that the risk of abdominal injury to pregnant women might be also reduced by using a seatbelt equipped with a pretensioner and force limiter.

There were some limitations to the present study. First, the safety of each method of seatbelt use was assessed using only a single test. However, the MAMA-2B dummy used in this study was developed for frontal MVC tests and resulted in highly reproducible results. Indeed, the MVC test for the accreditation of the dummy to the international standard was performed only once. Second, as the dummy represented the pregnant woman at 30 weeks of gestation, the result of our study applied for the pregnant woman with around this gestational age. However, our study provided information regarding the importance of correct conventional seatbelt use, as well as the effectiveness of the pretensioner and force limiter. Our findings might be generally applicable to rear-seat passengers in late-term pregnancy; in the future, the present result might be confirmed by analyzing the real-world MVCs involving pregnant passengers. Third, the front seatback was not present in our tests. Rear-seat passengers often contact their head or face on the front seatback during frontal collisions. Although there was no contact between the head or face and seatback in this study, the forward displacement of the body at the time of peak head excursion was measured. Further studies, in which the seatback angle or clearance between the body and front seatback is changed, will enable the likelihood of contact with the font seatback to be better assessed.

5. Conclusions

Crash tests using a dummy modelling late-term pregnancy assessed the safety of pregnant rear-seat passengers during a frontal collision. We confirmed the safety of a correctly used conventional lap-and-shoulder seatbelt, among various methods of seatbelt use for a pregnant passenger. Healthcare professionals must educate pregnant women about the correct use of conventional rear-seat safety belts, based on current scientific evidence. To reduce trunk injuries of pregnant rear-seat passengers, we propose the use of rear seatbelts equipped with a pretensioner and force limiter.

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