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Effectiveness Analysis of a Foldable Booster Safety Seat with Integrated Seatbelt Buckle for Reducing Children's Vehicle Accident Injury Risk

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Abstract: Vehicle collisions may result in severe injuries to child passengers. These accidents are of concern to the automotive community; hence child restraint systems are now subjected to legislative requirements. New foldable child safety seats are a new technology that has the potential for space-saving whilst protecting children from injuries. For the first time, this paper proposes to evaluate the safety of such a foldable seat, considering multiple frontal impact directions. The research created a baseline 6-year-old HybridIII child sled test computer model, built from a correlated vehicle rear seat cabin interior environment model and including its crash pulse characteristics, in which various seat safety configurations were evaluated. A total of seven scenarios were investigated, considering no booster seat, a traditional booster seat, and a foldable booster seat, combined with different impact angles, including frontal impact (0°), near and far side impacts (15° and 30°). In each scenario, the child kinematics, seatbelt to neck interaction, head acceleration, HIC_{15}, and chest acceleration were extracted as metrics to determine the safety effectiveness of the foldable booster seat. The study concluded that the foldable booster seat reduced the risk of neck entrapment as well as better restrained the dummy in its seat. While the head acceleration, HIC_{15}, and chest acceleration may slightly increase, injury responses caused by the foldable booster seat are still well within safe margins. This study suggests that foldable booster seats are innovative and practical and have the potential, pending more research, to protect children in frontal collisions better.

Keywords: Child safety; Foldable booster safety seat; Child restraint system; Traffic accidents; Multiple frontal impact directions;

1. Introduction

Vehicle accidents kill about 26,000 children and injure almost 10 million each year, making them the greatest cause of mortality and injury amongst children [1, 2]. As for the impact type, half of those

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accidents are frontal impacts [3, 4]. Furthermore, research has shown that head and chest injuries are the most common serious injuries children occupants suffer in vehicle collisions, leading to death or significant long-term disability [5, 6]. Evidence has suggested that child restraint systems could significantly reduce children's injuries in traffic accidents [7]. This has led to a series of legislative regulations for child restraint systems [8, 9], which have encouraged engineers and researchers to further investigate and implement solutions to improve the safety of children in traffic accidents.

Over the past decades, many essential research achievements have been made [10-12]. For instance, children's anthropomorphic test devices (ATDs), with their respective finite element models, were proposed as injury assessment tools to evaluate their injuries in traffic accidents to evaluate the effectiveness of child restraint systems, such as child safety seats and booster seats [13]. In 2009, Ren et al. [14, 15] proposed an integrated child safety seat design to solve this problem. However, the height of the integrated child safety seat needed to be continually modified based on the child passenger's height. This said the safety performance results of such integrated seats show that the 3-year-old, 6-year-old, and 10-year-old ATDs' injury responses were within the safe targets of child safety regulations.

A primary disadvantage of the integrated child safety seat, however, is that it cannot be disassembled when no children are in the vehicle, limiting vehicle usage and adding extra mass. The commonly used child safety seat is an independent structure installed on the car seat through the car seat belt or fixing system, which is inconvenient and unreliable to install [14]. Furthermore, such seats are child mass-dependent, requiring multiple purchases during the child's growth development.

The forward-facing child safety seat has attracted widespread attention, which can be removed from the car. Hu et al.[16] for example, **Error! Reference source not found.**investigated the effect of child seat design and its influence on reducing three-year-old children's injuries in a frontal collision. Four types of child seats for the frontal crash sled test were investigated, and it was concluded that five-point harness-type child seats presented a good performance.

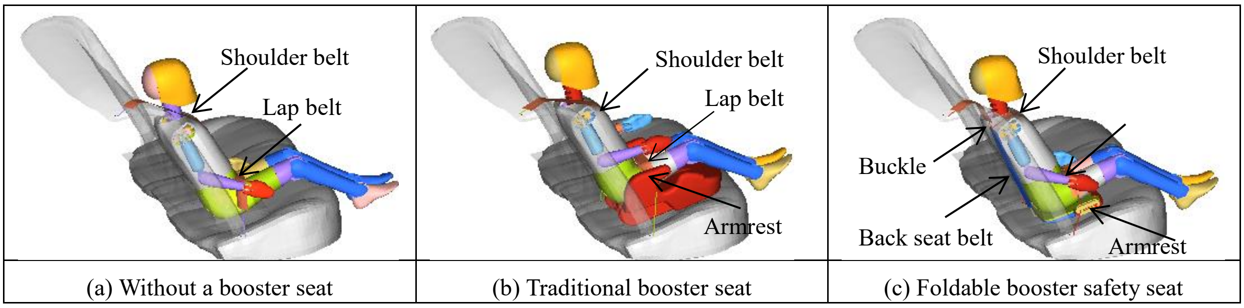
Yang et al. [17] carried out further research on forward-facing child safety seats and demonstrated that the child's head acceleration was reduced by 24% when the top ISOFIX fixing point was moved rearward by 0.25m combined with a more compliant anchorage fixing. Child seat material properties have also been investigated. Tellier et al. [3] compared two child restraint systems of a similar structure but different energy absorption materials. Their research indicated that improved energy absorption could reduce child brain loading.

Nevertheless, the large size of forward-facing child safety seats has become the main reason restricting their promotion (17.14% in Shanghai and Shenzhen, China) [18], leading to more research on developing more compact child seats. Cao et al. [19, 20] studied the safety of a booster seat and explored the effects of cushion height, stiffness, and friction values. Their results verified that the improved parameters of the cushion (height, stiffness and friction) for children of 6-year-old and 10-year-old children could improve the E-NCAP frontal collision score by 9.4% and 24.6%, respectively.

However, most of their investigations were based on a single impact type rather than considering different impact directions. Moreover, the current booster seat volume could be further reduced, making it foldable, as illustrated in Fig. 1. Unlike most traditional child booster safety seats, the armrests of the foldable booster safety seat can be pulled out according to the width of the child's hips to accommodate children of different anthropometry. At the same time, a buckle attached to the foldable booster seat can be connected to the seatbelt so that the slip ring position can be adjusted according to the shoulder height of the child's sitting position, as shown in Fig. 1, Fig. 2, and Fig. 3.

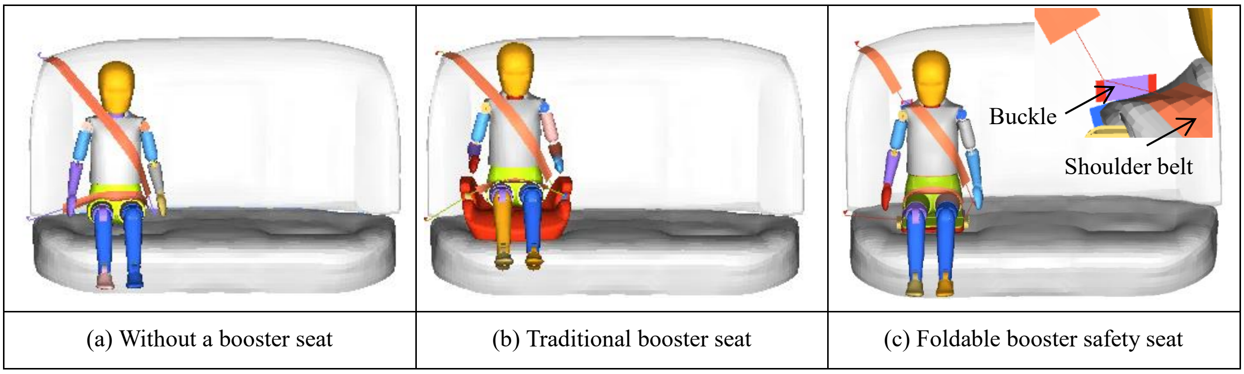
(a) Traditional booster | (b) Foldable booster (stored) | (c) Foldable booster (used)

Fig. 1 Traditional booster safety and seat foldable booster safety seat.



(a) Without a booster seat | (b) Traditional booster seat | (c) Foldable booster safety seat

Fig. 2 Side view of the dummy without and with children's safety seats.



(a) Without a booster seat | (b) Traditional booster seat | (c) Foldable booster safety seat

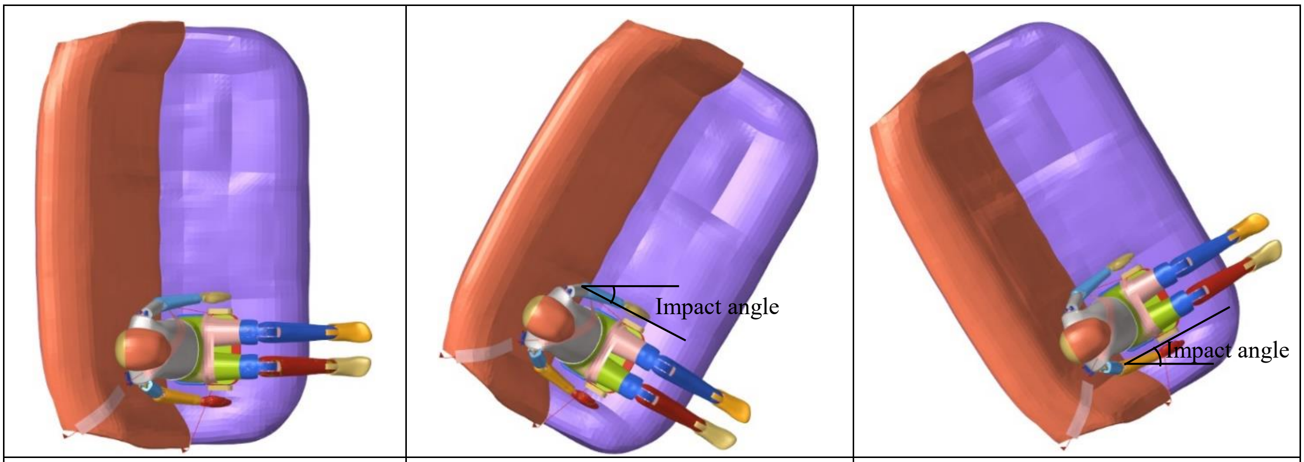
Fig. 3 Front view of the dummy without and with children's safety seats.

Conveniently, a foldable booster safety seat can be stored more easily. Despite all these advantages, such technology lacks safety assessment, which may restrict its deployment in the automotive market. To the best of the authors' knowledge, such foldable booster seats' safety effectiveness has not been investigated and reported.

This research aims to investigate the effectiveness of a foldable booster safety seat system against not using such technology. This article establishes a finite element model of a foldable booster safety seat under different collision angles. Head, HIC_{15}, and chest acceleration are adopted as injury criteria to assess its protective response, as well as the relationship between the seatbelt and the crash test dummy neck. It is the first study to examine the effects of foldable booster safety seats in reducing children's vehicle accident risk based on different impact angles.

2 Methods and Materials

70% of the frontal collisions, the most common form of collision, are offset collisions [21-24]. In the existing collision assessment procedures, the collision angle is mainly concentrated within 0° to 30°, such as the 0° collision proposed by C-NCAP and Euro-NCAP and the 15° / 30° collision angles proposed by FMVSS208. To analyze the effectiveness of a foldable booster safety seat, frontal collision sled tests on the frontal, nearside and far side with impact angles between 0°, 30°, and -30° were built up, as shown in Fig.4 [25]. In a nearside sled test, the child restraint system moves towards the door, while on the far side, it is moving away [26]. The sled tests were simulated with a Hybrid III 6-year-old child dummy, vehicle rear seat, and foldable booster safety seats using LS-DYNA software.



(a)Frontal | (b) Max nearside (30°) | (c) Max farside (30°)

Fig. 4 Frontal collision sled test system.

2.1 Traditional booster and foldable booster safety seat

A folded child safety seat finite element model was created based on a foldable booster safety seat shown in Fig. 1. The armrest is embedded within the seat like a drawer. When in use, the armrest can be adjusted according to the width of the child's hips, so it adapts to children of different body sizes. Besides, the foldable booster does not have Isofix system anchors, hence is not fixed to the car's structure. A seatbelt strap, including a buckle, is attached to the back of the foldable booster seat (Fig. 1 c). The buckle's height can be adjusted to accommodate the child's sitting position at shoulder height. Besides, when stored, the seatbelt strap can be wrapped around the cushion (Fig 1. b). When in use, the buckle can be used to secure the standard vehicle seatbelt at a suitable child's shoulder height.

Shell elements were used to model the seat outer layer and the armrests of the booster seats (traditional and foldable), while Hexa elements were employed to represent the seat foam. The materials for the outer covering of the traditional booster seat have been attributed to a thickness of 5 mm, with a plastic material behavior comparable to the dashboard of the Taurus vehicle finite element model provided by the National Crash Analysis Center (NCAC) library [27].

The foldable booster seat's outer covering and the armrests have been attributed to a thickness of 1.6 mm, with a material behavior provided by a seat manufacturer OEM. The material behavior of the traditional booster and the foldable one was presented in Fig.5. The seat foam material properties were modeled as a low-density foam, for which the information was extracted from the Taurus vehicle finite element. Fig. 6, Fig. 7 and Fig. 8 show the traditional booster and foldable booster safety seat model. Besides, the geometry of the rear seat comes from a validated NCAC model, and the traditional booster and foldable booster safety seat were built up based on the actual sample with equivalent material properties that are close to reality. Consequently, those children's safety seat systems are reasonably represented and are plausible.

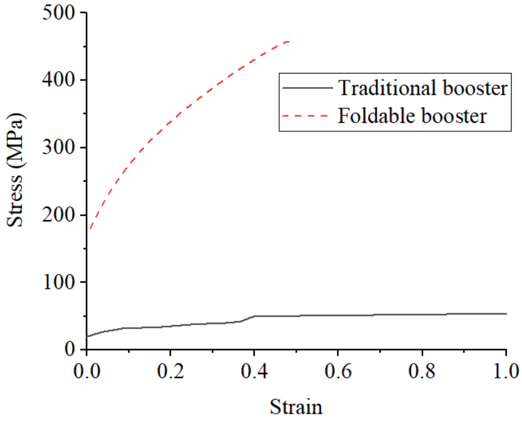
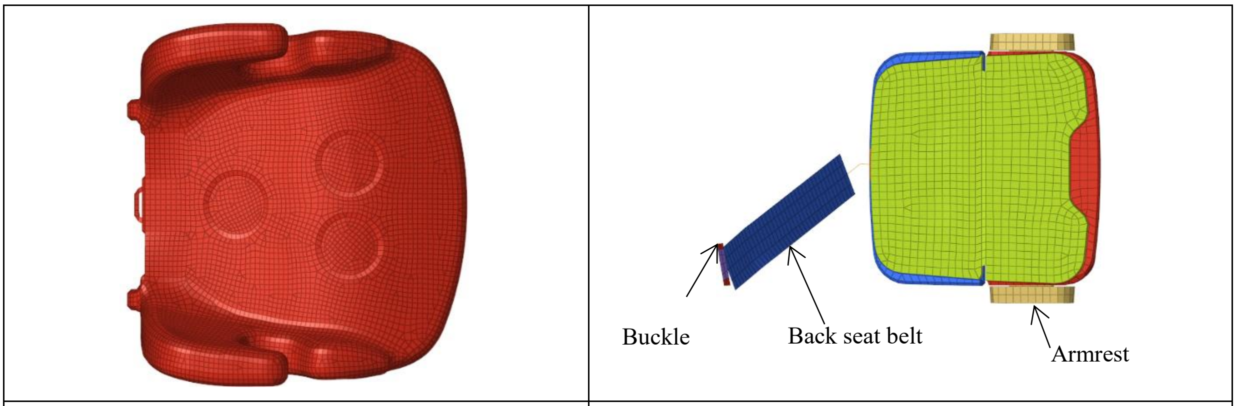


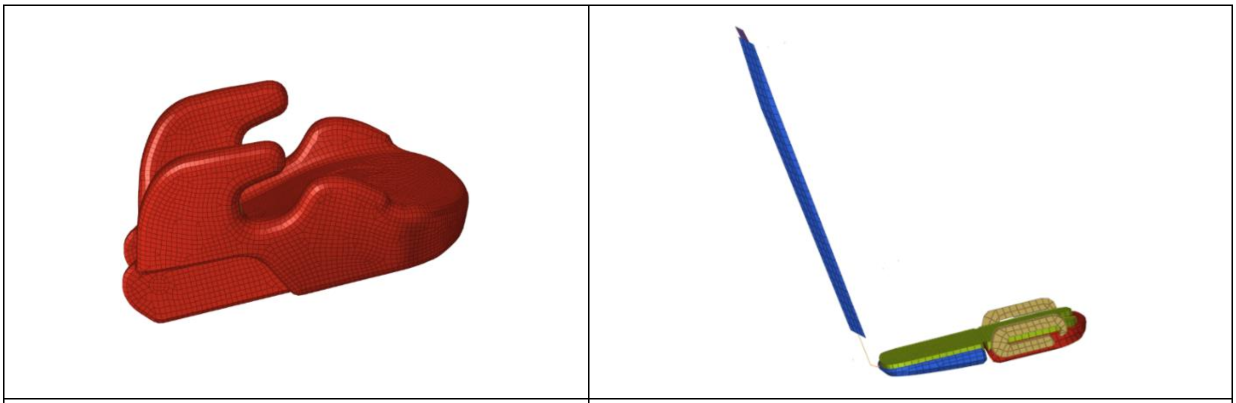
Fig. 5 Effective stress-strain curve of the traditional booster safety seat and the foldable booster safety seat cover (provided by seat

OEM).



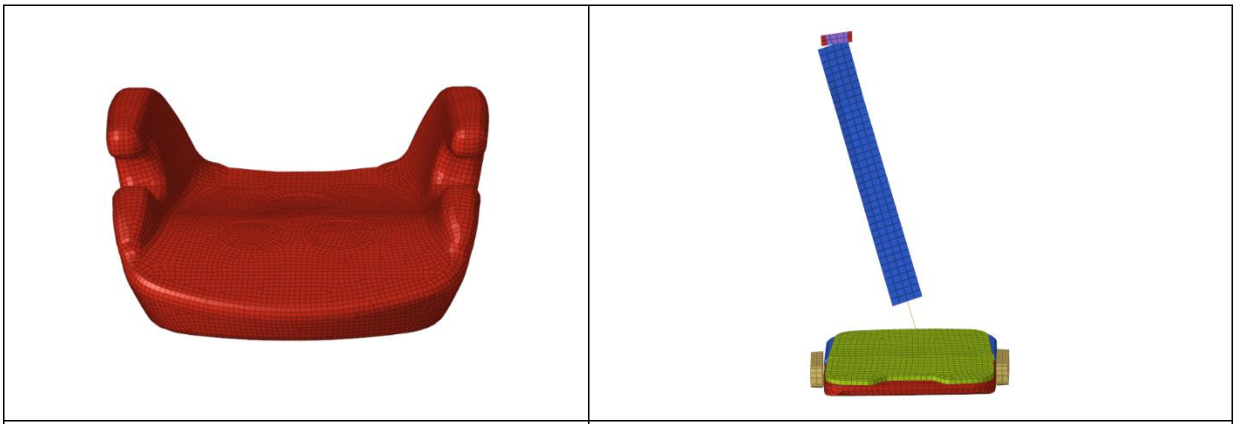
(a) Traditional booster (b) Foldable booster safety seat

Fig. 6 Top view of the traditional booster and foldable booster safety seat finite element model.



(a) Traditional booster (b) Foldable booster safety seat

Fig. 7 Side view of the traditional booster and foldable booster safety seat finite element model.



(a) Traditional booster (c) Foldable booster safety seat

Fig. 8 Front view of the traditional booster and foldable booster safety seat finite element model.

2.2 Sled test model

The sled tests model consists of a vehicle rear seat, a 6-year-old dummy, and a foldable child safety seat built up according to standard children's safety seat sled tests [15]. The safety belt on the car body is pulled out from its retractor, passed through the slip ring of the back seatbelt of the foldable booster safety seat, the dummy chest, and then through the armrest of the child seat after contacting the slip ring on the rear seat of the car. A typical acceleration data based on the Taurus frontal collision finite element model in an NHTSA rigid wall frontal 56km/h crash test [28], was applied as input to the sled test. The acceleration field experienced by the rear seat occupant is illustrated in Fig.9.

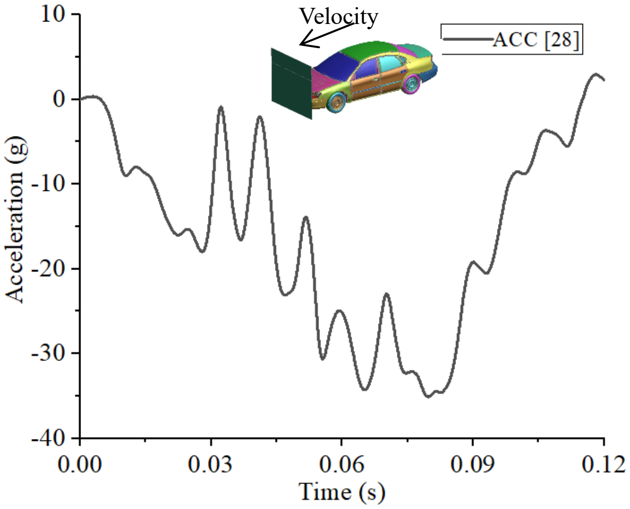


Fig. 9 Acceleration of the sled test model.

2.3 Effectiveness analysis

The objective of the present study is to evaluate the effectiveness of a foldable child safety seat. As such, the study will compare the kinematics and injury responses between a normally seated child occupant with a standard seatbelt, a child dummy with a traditional booster seat, and a child occupant sitting on a foldable booster seat. The safety comparison will be performed using a Hybrid III 6-year-old dummy injury in the configurations above in multiple impact directions, as previously discussed, considering head acceleration, HIC_{15}, and chest acceleration [29-31]. As previous research indicated that a shoulder belt could strangle the occupant and give poor performance in restraining children effectively, causing potential casualties [32], the study will also review the seatbelt interaction with the dummy's neck. The simulation plan was listed in the Table 1.

Table 1. Summary of simulation plan.

	Content
Dummy	6-year-old HybridIII
Simulated object	Dummys without and with booster seat (traditional and foldable)
Impact angle	frontal impact (0°), near and far side impacts (15° and 30°)
Metrics	Kinematics, seatbelt to neck interaction, head acceleration, HIC_{15}, and chest acceleration

3 Results

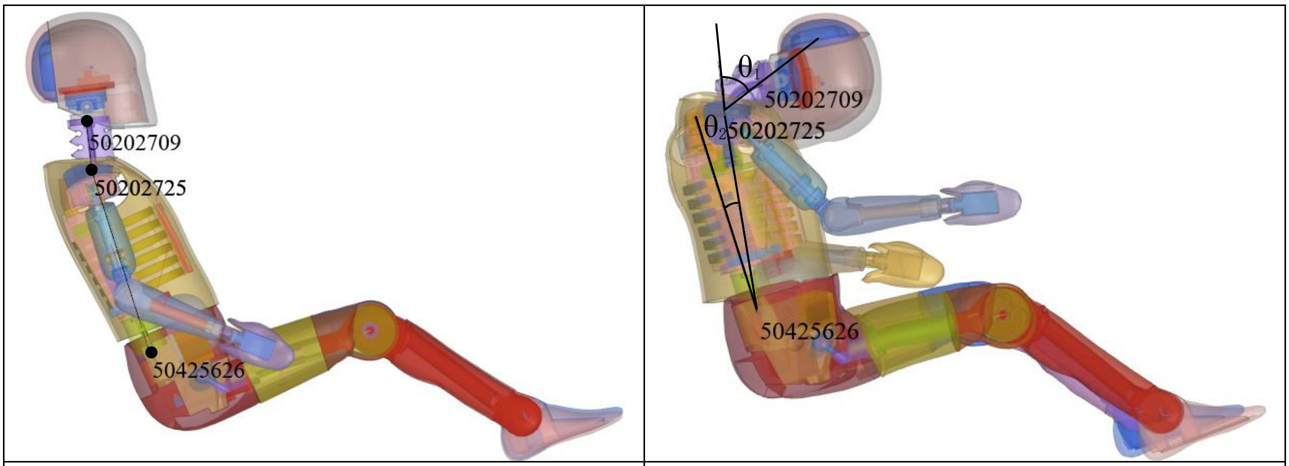
3.1 Effectiveness of the foldable booster safety seats in the frontal impact (0°)

3.1.1 Kinematics in the frontal impact

The kinematic positions are illustrated in Fig. 11, Fig. 12, and Fig. 13, suggesting that dummies are restrained in all three scenarios. Besides, the dummies moved forward and rotated around the pelvis during the collision. Fig. 10 (a) depicted the rotation angle measurement points, while Fig. 10(b) demonstrated the angles measured for head rotation (θ_1) and upper extremity rotation (θ_2). The θ_1 represents the angle formed by the connection line connecting a node on the superior cervical spine to a node on the lower cervical spine prior to and after impact (Fig. 10). The θ_2 represents the angle formed by the connection line connecting a node in the lower cervical spine to a node in the lower lumbar spine before and after impact (Fig. 10).

Fig. 14, Fig. 15 and Table 2 demonstrated that the highest head rotation (86.6°) which was obtained from the dummy using the traditional booster safety seat model is 45.8% higher than that of the dummy without using a booster (59.4°), while the head rotation of the dummy using foldable booster seat (71.7°) is 20.7% higher than that of the dummy without using a booster. Additionally, the dummy using the traditional booster seat illustrated the highest upper extremity rotation (37.4°), which is 340.0% larger than that of the dummy without using a booster (8.5°). Besides, the dummy using the foldable booster seat (16.7°) is 96.5% larger than that of the dummy without using a booster seat. It was observed that a more pronounced rotation of the upper extremity is evidenced in the traditional booster seat configuration, resulting in no shoulder belt contact with the dummy's neck.

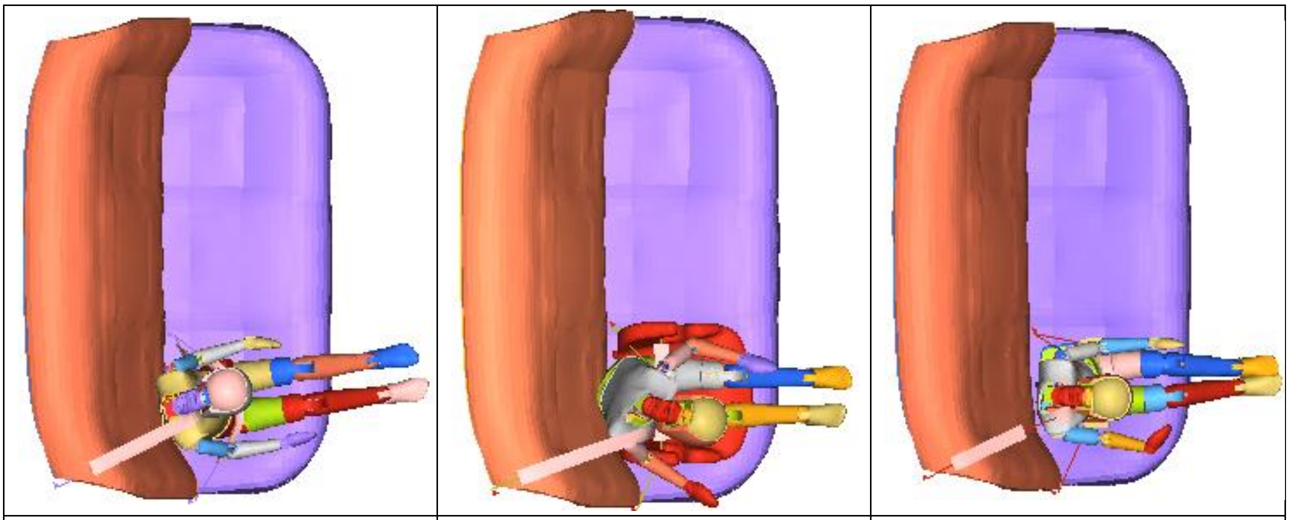
Furthermore, the edges of the shoulder belt make a slight interaction with the dummy's neck using the foldable booster safety seat. While the "without a booster case" scenario, on the other hand, generates a more significant contact with the dummy's neck (a quarter-width of the shoulder belt), as shown in Fig. 12. Moreover, the strangling is considered as the qualitative overlap/ contact of the seatbelt against the crash dummy neck herein. The higher the overlap, the highest the risk of potential for strangulation. Thus, the dummy without a booster seat suffered the highest risk of being strangled by the shoulderbelt, while the dummy using the foldable booster seat illustrated the lowest risk.



(a) Measurement points

(b) Head and upper extremity rotation angles

Fig. 10 Measurements used for children' rotation metrics.

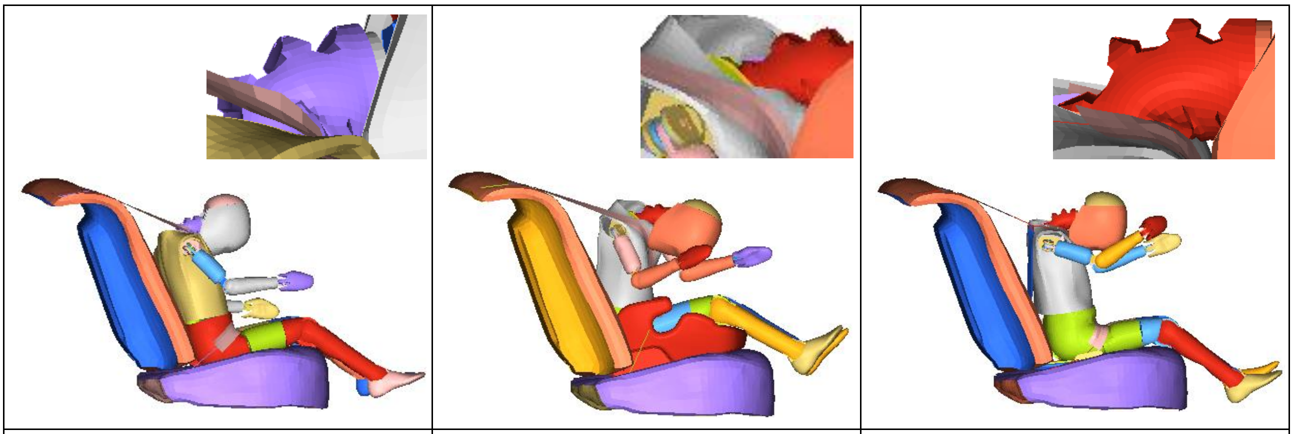


(a) Without booster

(b) Traditional booster

(c) Foldable booster

Fig. 11 Top view of child restraint systems in the frontal impact.

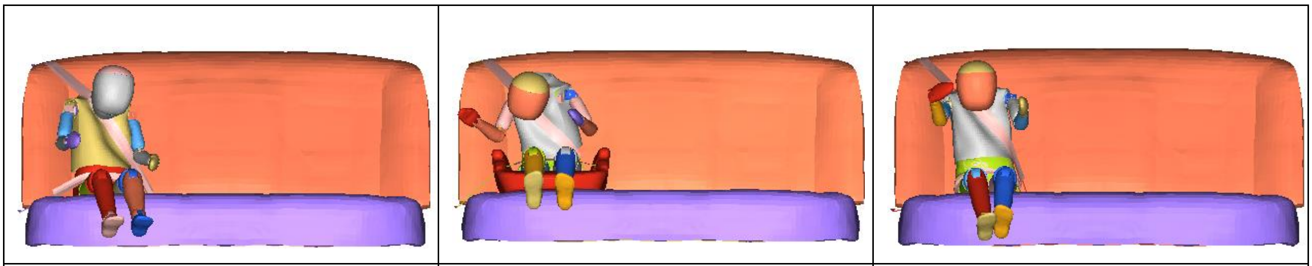


(a) Without booster

(b) Traditional Booster

(c) Foldable booster

Fig. 12 Side view of child restraint systems in the frontal impact.



(a) Without booster

(b) Traditional Booster

(c) Foldable booster

Fig. 13 Front view of child restraint systems in the frontal impact.

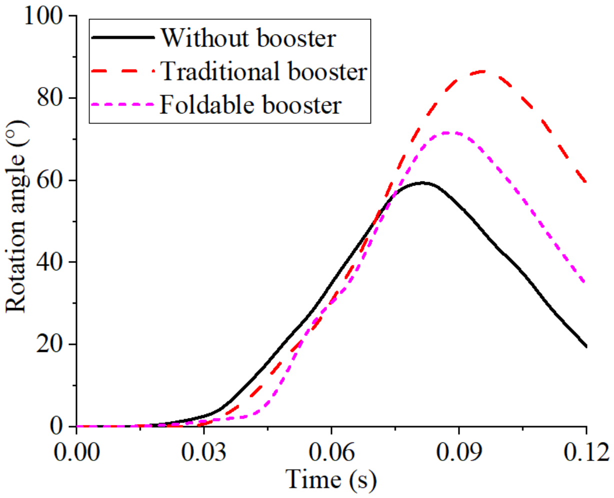


Fig. 14 Children's head rotation in the frontal impact.

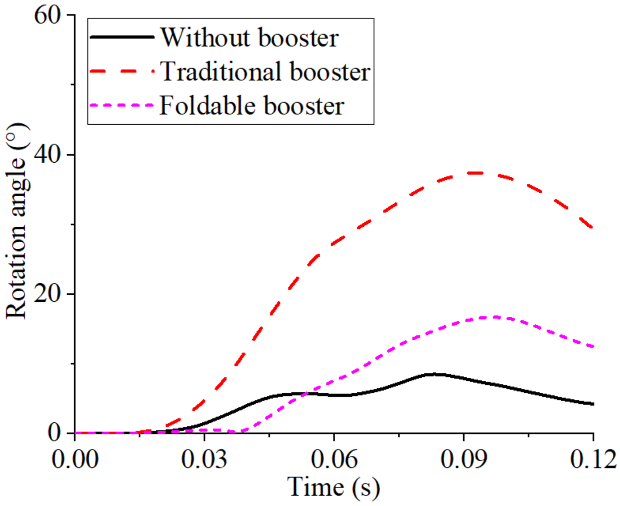


Fig. 15 Children's upper extremity rotation in the frontal impact.

Table 2. Summary of children's maximum rotation for frontal impact loadcase.

	Without booster	Traditional booster	Foldable booster
Head rotation	59.4°	86.6°	71.7°
Percentage variations	0	45.8%	20.7%
Upper extremity rotation	8.5°	37.4°	16.7°
Percentage variations	0	340%	96.5%

3.1.2 Injuries in the frontal impact

The injury responses for the head and the chest are illustrated in Fig 16, Fig 17, and Table 3. The results demonstrate that the traditional booster safety seat scenario generates the lowest head peak acceleration (35.3g), HIC_{15} (205.6), and peak chest acceleration (15.0g) which is -16.5%, -18.6%, -8.5% lower than those of the dummy without using a booster seat (42.3g head peak acceleration, 252.6 HIC_{15}, and 16.4g chest peak acceleration). In the foldable booster safety case, the head acceleration is higher (48.6g), the HIC_{15} is lower (226.1), and chest peak acceleration is higher (32.2g) compared to the case without the booster seat, giving a difference of 14.9%, -10.5% and 96.3%.

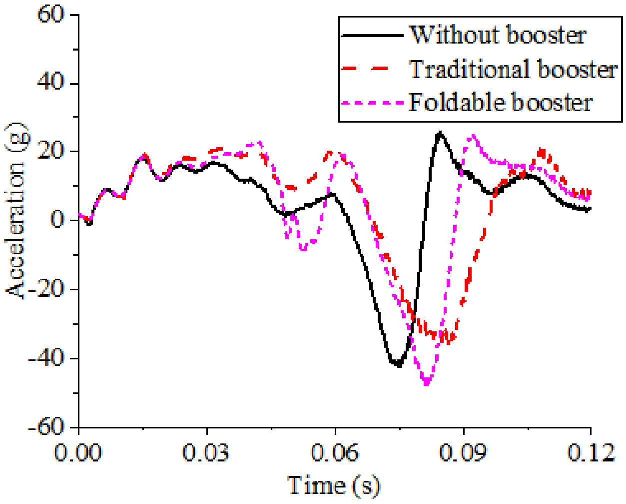


Fig. 16 Children's head acceleration in the frontal impact.

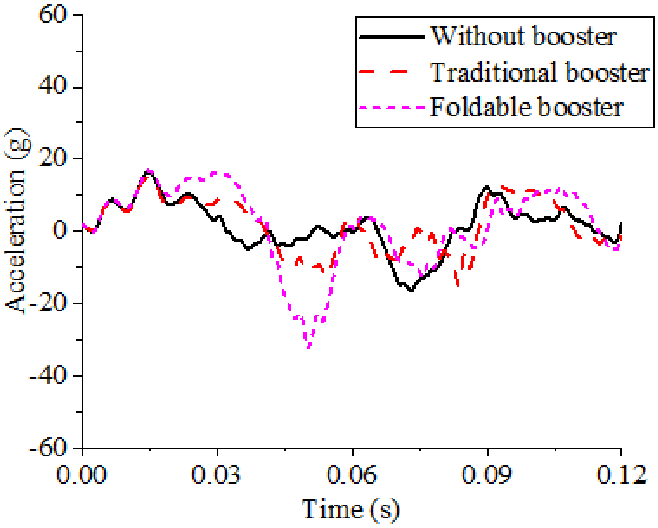


Fig. 17 Children's chest acceleration in the frontal impact.

Table 3. Summary of injuries for frontal impact loadcase.

	Without booster	Traditional booster	Foldable booster	Accepted level (FMVSS 208)
Head acceleration	42.3g	35.3g	48.6g	--
Percentage variations	0	-16.5%	14.9%	--
HIC_{15}	252.6	205.6	226.1	700
Percentage variations	0	-18.6%	-10.5%	--
Chest acceleration	16.4g	15.0g	32.2g	60g
Percentage variations	0	-8.5%	96.3%	--

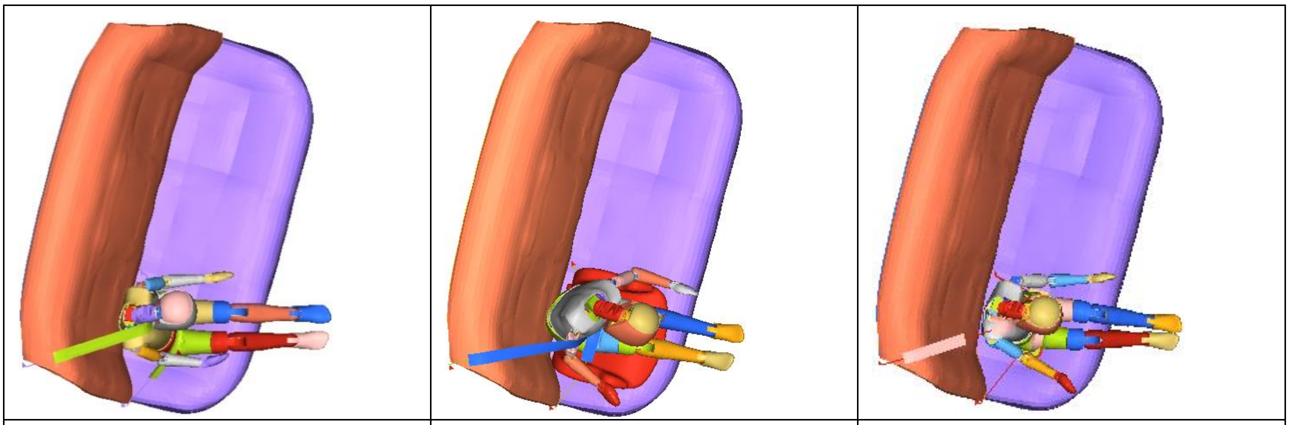
3.2 Effectiveness of the foldable booster safety seats in frontal nearside impact (15° and 30°)

3.2.1 Kinematics in 15° frontal nearside impact.

Fig. 18, Fig. 19, and Fig. 20 illustrate the dummy's kinematics. In the case of the foldable booster seat, only a minor rotation about the vertical axis could be observed, while in the two other cases, this rotation is more pronounced. In the without booster seat scenario, this rotation reduces the space between the seat belt and the dummy's neck, leading to the shoulder belt potentially injuring the dummy's neck by strangulation, as shown in Fig. 19(a). Besides, the traditional booster seat is wider than the dummy, which gives the dummy clearance to move laterally. Consequently, the lap belt cannot effectively limit the tendency of the dummy to slide forward slightly diagonally.

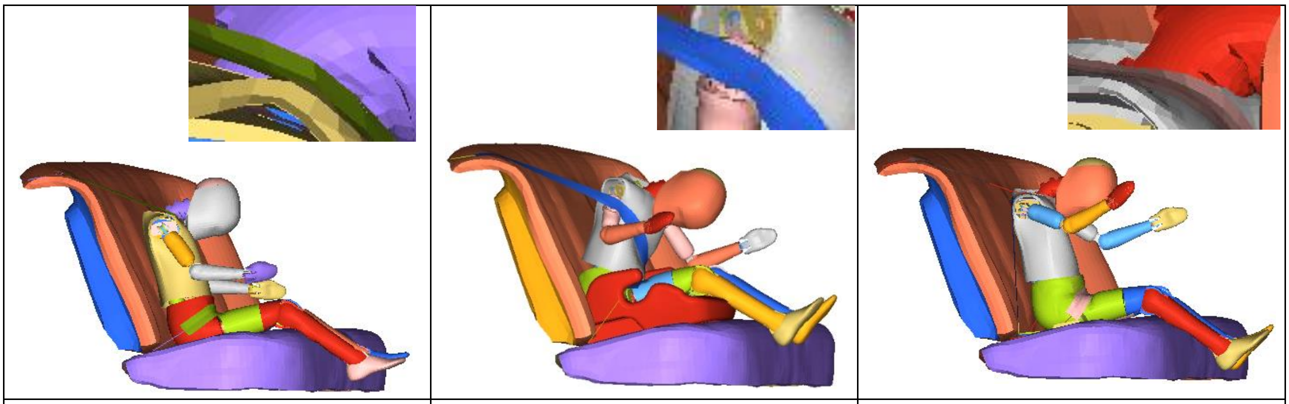
The children's rotation was shown in Fig. 21, Fig. 22, and Table 4, which showed that the dummy using the traditional booster seat had the highest head rotation (82.4°), which was 34.9% higher than the dummy without a booster seat's (61.1°), and that the dummy using the foldable booster seat had the largest head rotation (67.5°), which was 10.5% higher than the dummy without a booster seat's. Furthermore, the dummy utilizing the traditional booster seat showed the largest upper extremity rotation (45.7°), which is 311.7% greater than the rotation of the dummy not using a booster (11.1°). Additionally, the dummy's upper extremity rotation (15.8°) while utilizing the folding booster seat is 42.3% greater than it would be in the situation without a booster one.

Thus, the dummy employing a traditional booster safety seat experienced a much more noticeable rotation, resulting in the upper extremity sliding away from the shoulder belt. However, the dummy using the foldable booster safety seat exhibited a lesser rotation angle around the Z-axis, resulting in no contact between the neck and the shoulder belt. The dummy was, thus, restrained better in the foldable booster safety seat, indicating that the dummy using a foldable booster seat shows the lowest risk of being strangled by the shoulder belt.



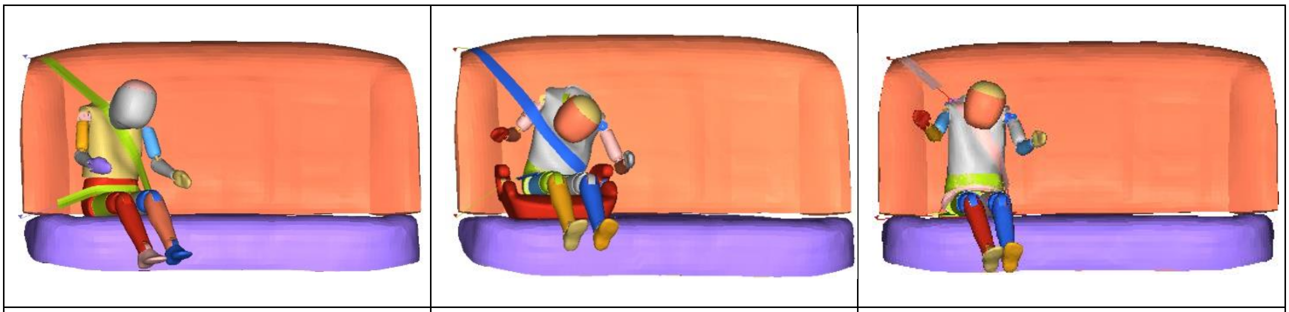
(a) Without booster | (b) Traditional booster | (c) Foldable booster

Fig. 18 Top view of child restraint systems in 15° frontal nearside impact.



(a) Without booster | (b) Traditional booster | (c) Foldable booster

Fig. 19 Side view of child restraint systems in 15° frontal nearside impact.



(a) Without booster | (b) Traditional booster | (c) Foldable booster

Fig. 20 Front view of child restraint systems in 15° frontal nearside impact.

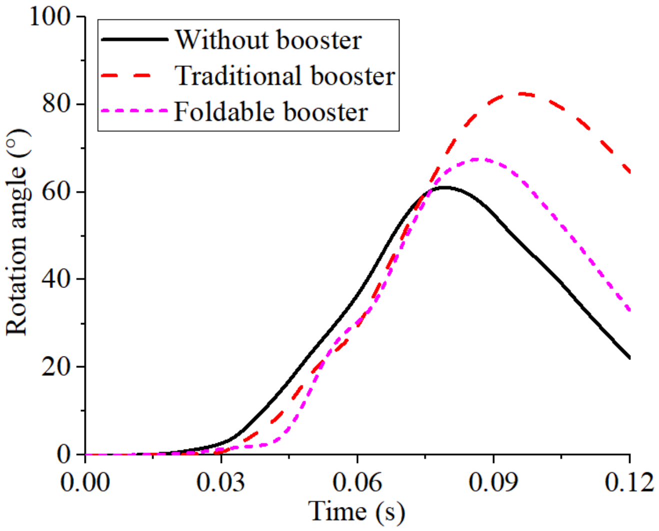


Fig. 21 Children's head acceleration in 15° frontal nearside impact.

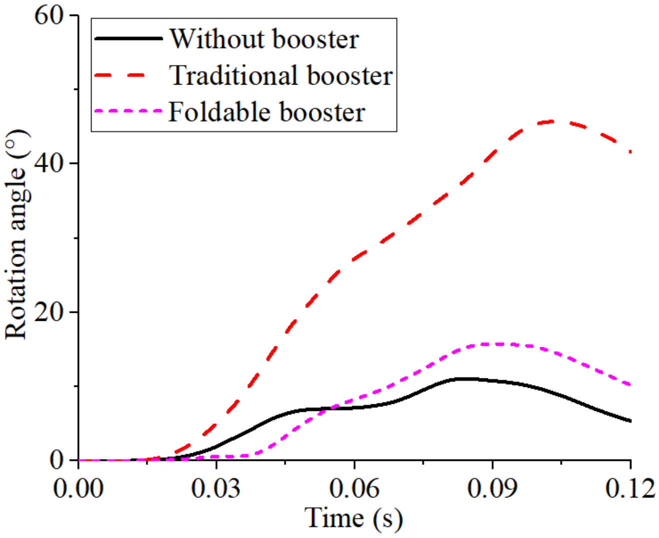


Fig. 22 Children's upper extremity rotation acceleration in 15° frontal nearside impact.

Table 4. Summary of children's maximum rotation for 15° frontal nearside impact.

	Without booster	Traditional booster	Foldable booster
Head rotation	61.1°	82.4°	67.5°
Percentage variations	0	34.9%	10.5%
Upper extremity rotation	11.1°	45.7°	15.8°
Percentage variations	0	311.7%	42.3%

3.2.2 Injuries in 15° frontal nearside impact.

Fig. 23 and Fig. 24 show the dummy injury responses. Using the traditional booster leads to higher head and chest accelerations than those without a booster seat. On the one hand, compared to a seat without a booster (39.7g, 165.6, and 16.4g, respectively), the traditional booster case's head acceleration, HIC15, and chest accelerations (42.5g, 208.1g, and 19.5g, respectively) are greater by

7.1%, 25.7%, and 18.9%, respectively. The dummy with the folding booster safety seat, however, had greater HIC15 (224.1), peak chest acceleration (35.7g), and peak head acceleration (45.2g) compared to the case without the booster, resulting in differences of 13.9%, 35.3%, and 117.7%, respectively. Table 5 describes the summary of maximum injuries observed in the 15° frontal nearside impact scenarios.

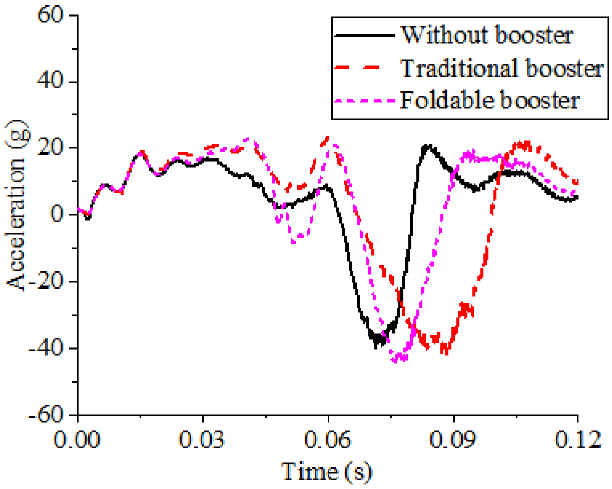


Fig. 23 Children's head acceleration in 15° frontal nearside impact.

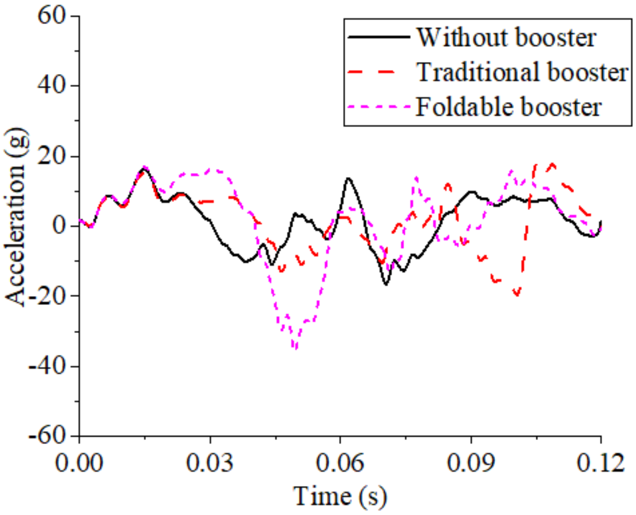


Fig. 24 Children's chest acceleration in 15° frontal nearside impact.

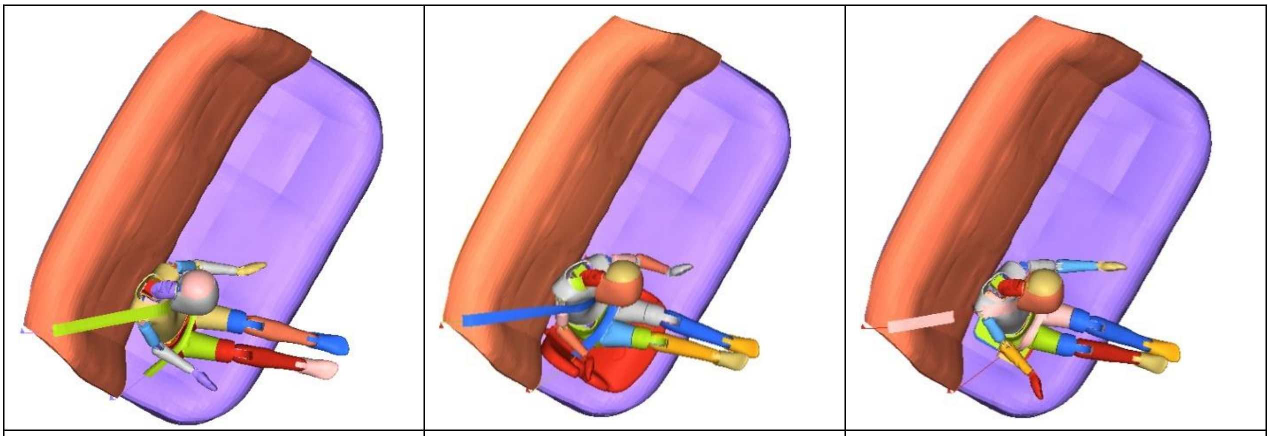
Table 5. Summary of injuries for 15° frontal nearside impact load case.

	Without booster	Traditional booster	Foldable booster	Accepted level (FMVSS 208)
Head acceleration	39.7g	42.5g	45.2g	--
Percentage variations	0	7.1%	13.9%	--
HIC_{15}	165.6	208.1	224.1	700
Percentage variations	0	25.7%	35.3%	--
Chest acceleration	16.4g	19.5g	35.7g	60g
Percentage variations	0	18.9%	117.7%	--

3.2.3 Kinematics 30° frontal nearside impact.

The dummies' kinematic positions are shown in Fig. 26, Fig. 27 and Fig. 28. In the 30° frontal nearside impact case, the dummy sustained a more significant tilt toward the inboard side of the vehicle than in the 15° frontal nearside impact. Meanwhile, no dummy appears to be strangled by the shoulder belt. Fig. 29, Fig. 30 and Table 6, which illustrated the rotation of the children, demonstrated that the highest head rotation (61.6°) obtained from the dummy using the foldable booster safety seat model is 4.6% higher than that of the dummy without using a booster (58.9°), while head rotation of the dummy using the traditional booster seat (53.1°) is 9.8% smaller than the without booster case. Additionally, the highest upper extremity rotation (25.9°) which was obtained from the dummy using the traditional booster seat is 27.6% larger than that of the dummy without using a booster (20.3°). The upper extremity rotation of the dummy using the foldable booster seat (14.5°) is 28.6% lower than the without booster case.

Thus, the dummy using a booster seat (traditional and foldable) presented a larger rotation than the dummy without a booster. Furthermore, the dummy with the traditional booster safety seat leaned to the left and escaped from the shoulder belts, while the dummy with the foldable booster safety seat experienced lesser rotation and remained in its seat.

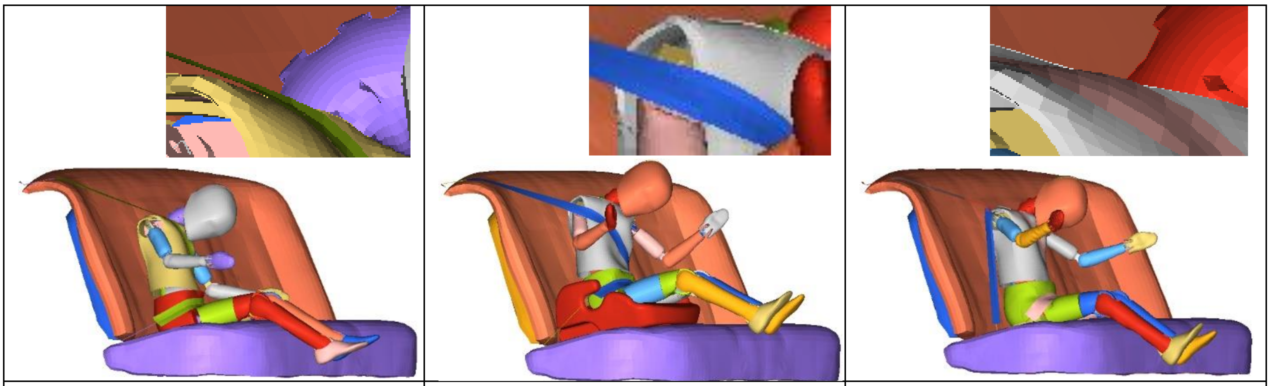


(a) Without booster

(b) Traditional booster

(c) Foldable booster

Fig. 26 Top view of child restraint systems in 30° frontal nearside impact.

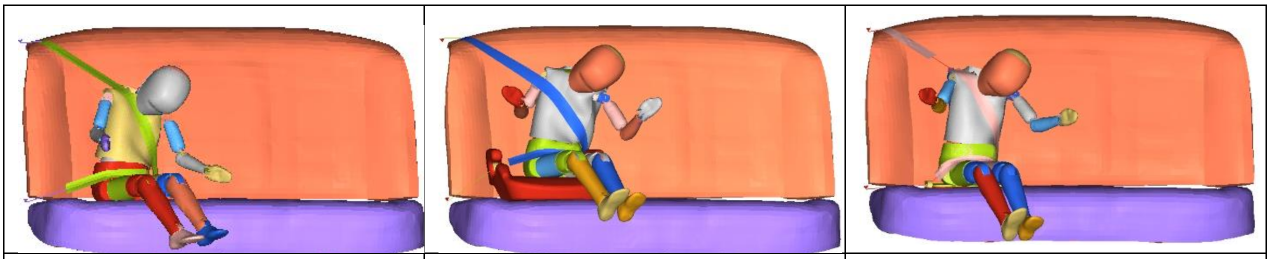


(a) Without booster

(b) Traditional booster

(c) Foldable booster

Fig. 27 Side view of child restraint systems in 30° frontal nearside impact.



(a) Without booster

(b) Traditional booster

(c) Foldable booster

Fig. 28 Front view of child restraint systems in 30° frontal farside impact.

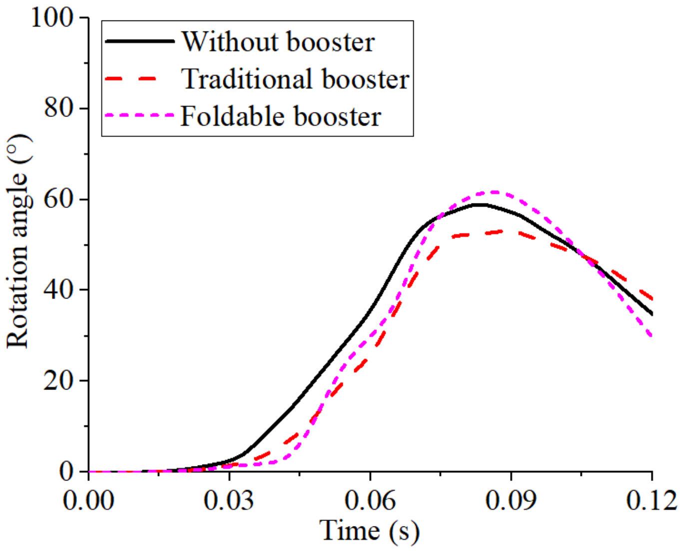


Fig. 29 Children's head acceleration in 30° frontal nearside impact.

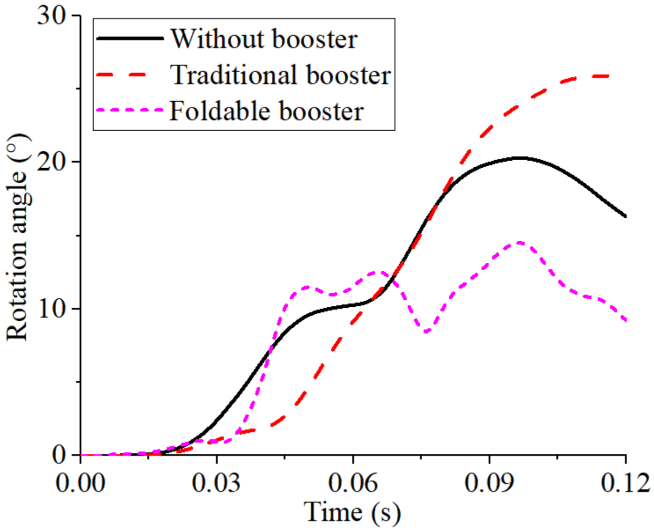


Fig. 30 Children's upper extremity rotation acceleration in 30° frontal nearside impact.

Table 6. Summary of children's maximum rotation for 30° frontal nearside impact.

	Without booster	Traditional booster	Foldable booster
Head rotation	58.9°	53.1°	61.6°
Percentage variations	0	-9.8%	4.6%
Upper extremity rotation	20.3°	25.9°	14.5°
Percentage variations	0	27.6%	-28.6%

3.2.4 Injuries 30° frontal nearside impact.

Injury responses are depicted in Fig. 31 and Fig. 32. A summary of maximum injuries observed in the 30° frontal nearside impact scenarios is listed in Table 7. The results suggested that the foldable boosters secured the children in the seat, hence leading to a more positive interaction with the restrain system, increasing head acceleration, HIC_{15}, and chest acceleration (59.7g, 258.8, and 32.9g, respectively) compared to the without booster case (37.5g, 234.7, 15.7g), giving a difference of 59.2%, 10.3%, and 109.6%. Besides, the traditional booster safety seat scenario dummy (46.5g, 184.7, and 34.5g, respectively) gave a difference of 24.0%, -21.3%, and 10.3% compared to the without booster case head acceleration, HIC_{15}, and chest acceleration.

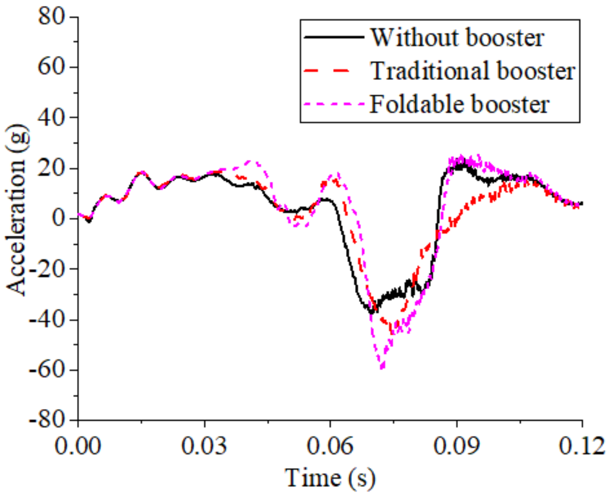


Fig. 31 Children's head acceleration in 30° frontal nearside impact.

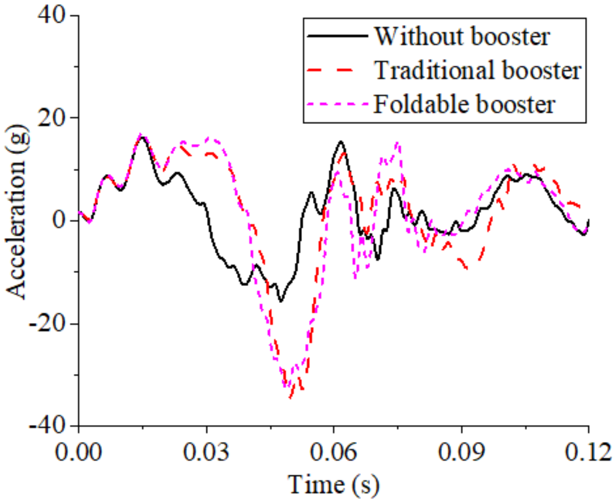


Fig. 32 Children's chest acceleration in 30° frontal nearside impact.

Table 7. Summary of injuries for 30° frontal nearside impact load case.

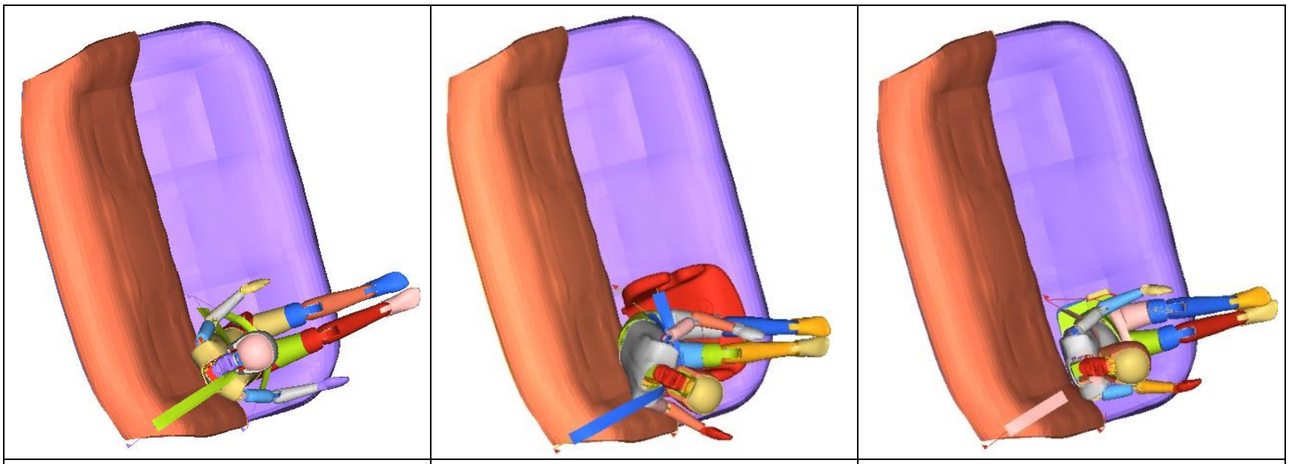
	Without booster	Traditional booster	Foldable booster	Accepted level (FMVSS 208)
Head acceleration	37.5g	46.5g	59.7g	--
Percentage variations	0	24.0%	59.2%	--
HIC_{15}	234.7	184.7	258.8	700
Percentage variations	0	-21.3%	10.3%	--
Chest acceleration	15.7g	34.5g	32.9g	60g
Percentage variations	0	119.7%	109.6%	--

3.3 Effectiveness of the foldable booster safety seats in frontal far side impact

3.3.1 Kinematics in 15° frontal far side impact.

The kinematic positions of the dummies in the 15° farside impact were depicted in Fig. 33, Fig. 34, and Fig. 35. The results depicted that dummies have shown a tilt outboard to the right. Additionally, Fig. 36, 37, and Table 8, which depicted the rotation of the children, revealed that the dummy using the traditional booster safety seat had the most head rotation (92.8°), which is 69.7% greater than the dummy not using the booster (54.7°). And the dummy's head rotation with a foldable booster seat (69.2°) is 26.5% greater than without a booster case. Furthermore, the highest upper extremity rotation (39.9°) obtained from the dummy using the standard booster seat is 295.0% greater than that of the dummy without using a booster (10.1°), while the folding booster seat (22.2°) is 119.8% greater than the without booster case.

Besides, the greater the rotation angle, the greater the probability of serious contact between the neck and the seat belt. When using the foldable booster safety seat, only the edge of the shoulder belts was in contact with the dummy's neck (Fig 34 (c)), while the shoulder belt did not contact the dummy's neck in the traditional booster case (Fig 34 (b)). Furthermore, the dummy using a foldable booster safety seat withstood a minor rotation compared to a traditional one. In the "without a booster case" scenario, the edge of the shoulder belt was rolled up, and one-third width of the shoulder belt came into contact with the neck, as illustrated in Fig 34 (a).

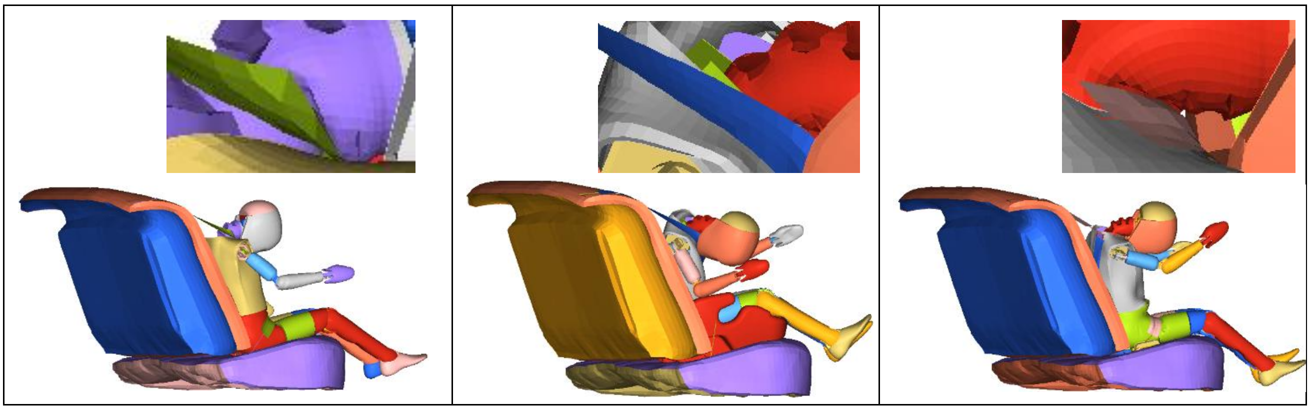


(a) Without booster

(b) Traditional booster

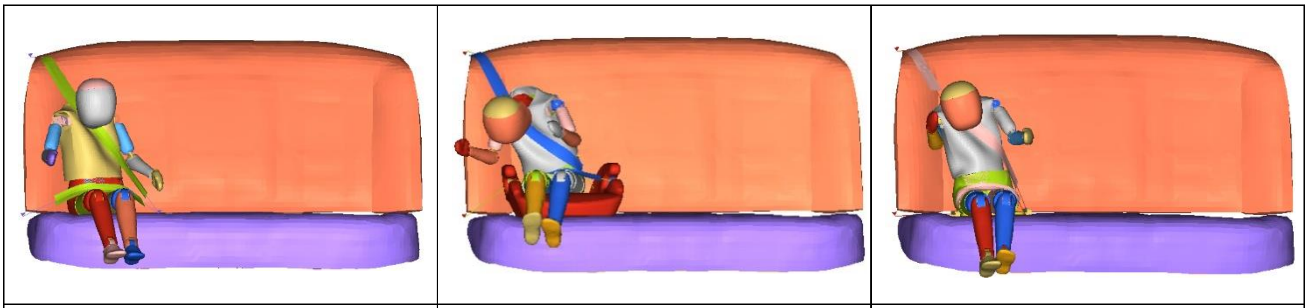
(c) Foldable booster

Fig. 33 Top view of child restraint systems in 15° frontal farside impact.



(a) Without booster	(b) Traditional booster	(c) Foldable booster

Fig. 34 Side view of child restraint systems in 15° frontal farside impact.



(a) Without booster (b) Traditional booster (c) Foldable booster

Fig. 35 Front view of child restraint systems in 15° frontal farside impact.

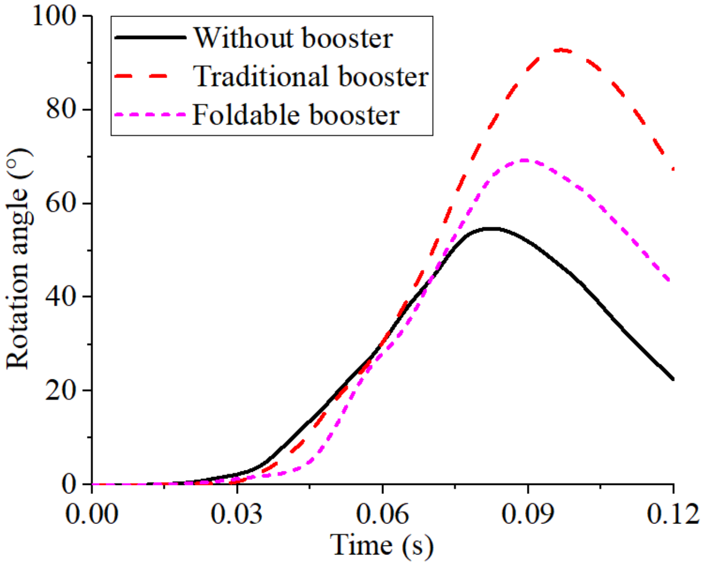


Fig. 36 Children's head acceleration in 15° frontal farside impact.

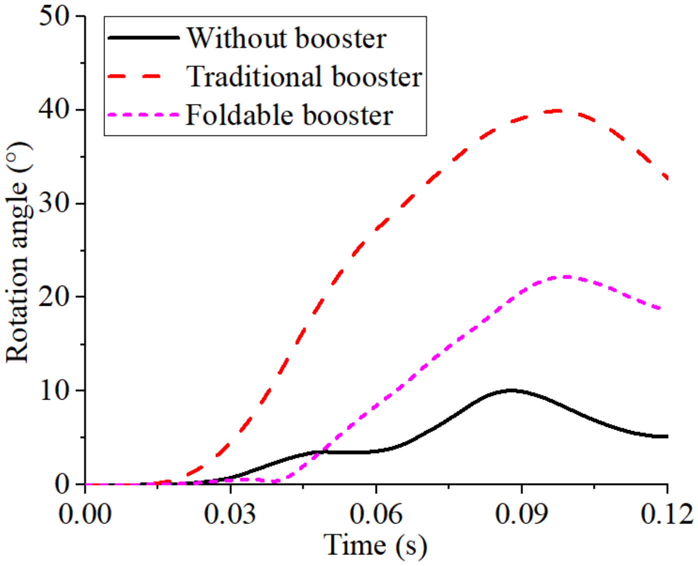


Fig. 37 Children's upper extremity rotation acceleration in 15° frontal farside impact.

Table 8. Summary of children's maximum rotation for 15° frontal farside impact loadcase.

	Without booster	Traditonal booster	Foldable booster
Head rotation	54.7°	92.8°	69.2°
Percentage variations	0	69.7%	26.5%
Upper extremity rotation	10.1°	39.9°	22.2°
Percentage variations	0	295.0%	119.8%

3.3.2 Injuries in the 15° frontal far side impact.

The head and chest acceleration injury responses are illustrated in Fig. 38 and Fig. 39. In the foldable booster safety case, the head acceleration (49.4g), the HIC_{15} (221.9), and the chest peak acceleration (26.6g) are higher compared to the case without the booster seat (43.5g, 168.3, and 16.2g), giving a difference of 13.6%, 31.8%, and 64.2%. Additionally, the dummy with the traditional booster safety seat situation (41.3g head acceleration, 206.8 HIC_{15}, and 14.2g chest acceleration) gives a difference of -5.1%, 22.9%, and -12.3% from the without booster seat situation. The maximum injuries observed in 15° frontal far side impact scenarios are summarized in Table 9.

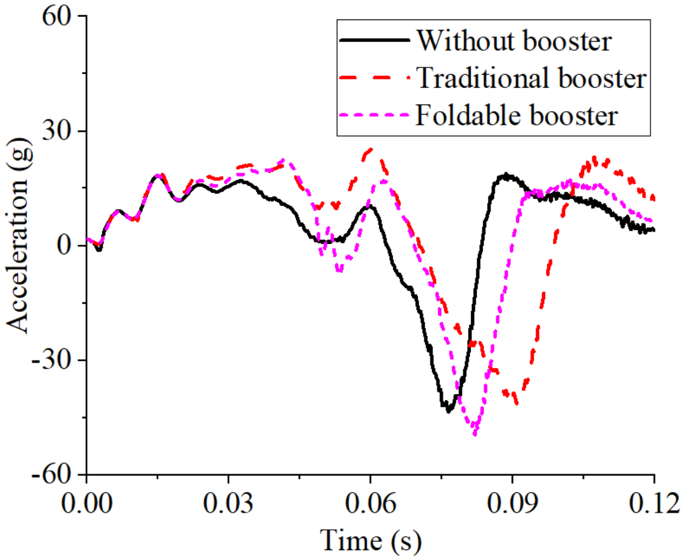


Fig. 38 Children's head acceleration in 15° frontal farside impact.

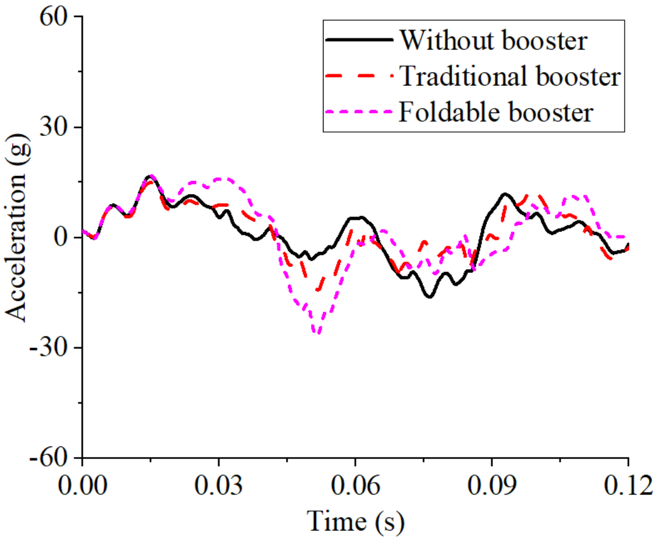


Fig.39 Children's chest acceleration in 15° frontal far side impact.

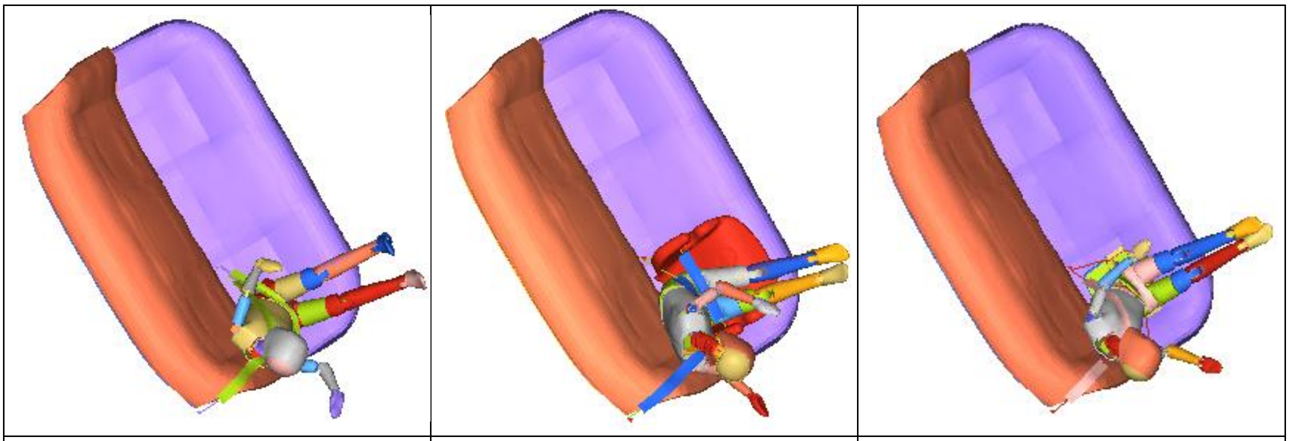
Table 9. Summary of injuries for 15° frontal far side impact loadcase.

	Without booster	Traditional booster	Foldable booster	Accepted level (FMVSS 208)
Head acceleration	43.5g	41.3g	49.4g	--
Percentage variations	0	-5.1%	13.6%	--
HIC_{15}	168.3	206.8	221.9	700
Percentage variations	0	22.9%	31.8%	--
Chest acceleration	16.2g	14.2g	26.6g	60g
Percentage variations	0	-12.3%	64.2%	--

3.3.3 Kinematics in 30° frontal far side impact

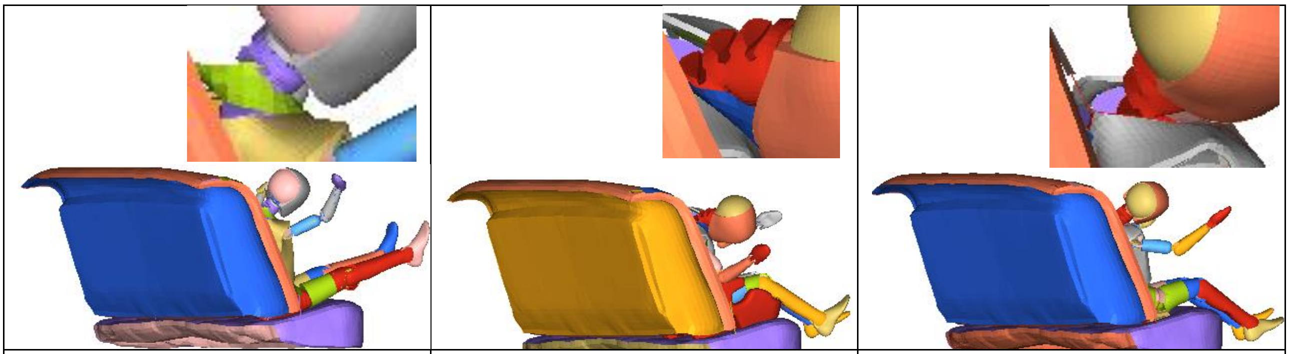
Fig. 40, Fig. 41, and Fig. 42 depicted the dummies' kinematics, which shows a tilt to the right. Besides, Fig. 43, Fig. 44, and Table 10 which illustrated the rotation of the children demonstrated that the highest head rotation (96.2°) was obtained from the dummy using the traditional booster safety seat model, which is 98.8% greater than that of the dummy without a booster (48.4°), whereas the head rotation of the dummy using a foldable booster seat (63.4°) is 31.0% greater than the without booster case. In addition, the greatest upper extremity rotation (42.6°) of the dummy using the traditional booster seat is 147% more than that of the dummy without a booster (17.2°). In addition, the upper extremity rotation of the dummy while using the foldable booster seat is 61% more than when the dummy is not utilizing a booster seat.

Thus, the rotation of the dummy using the foldable booster seat is smaller than that of the dummy using the traditional booster seat but more significant than the rotation of the dummy without using a booster seat. Besides, the three dummies contacted the shoulder belt. The dummy using the foldable booster seat and the traditional booster seat only made contact with the edge of the shoulder belts, while in the other configurations, the entire width of the shoulder belt contacted the neck.



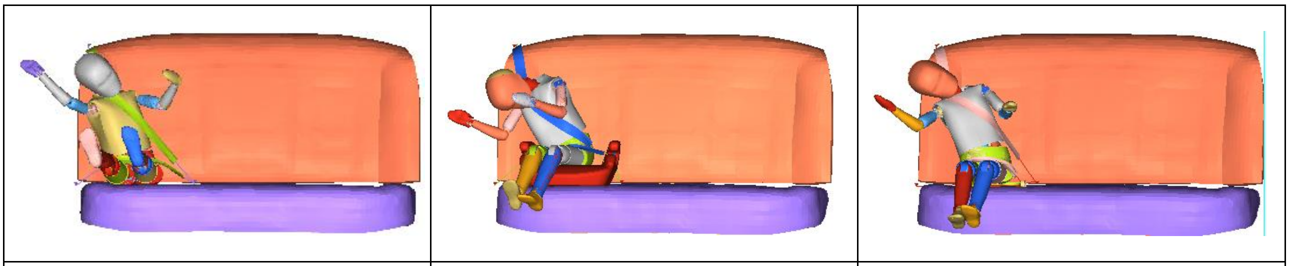
(a) Without booster (b) Traditional booster (c) Foldable booster

Fig. 40 Top view of child restraint systems in 30° frontal far side impact.



(a) Without booster (b) Traditional booster (c) Foldable booster

Fig. 41 Side view of child restraint systems in 30° frontal far side impact.



(a) Without booster (b) Traditional booster (c) Foldable booster

Fig. 42 Front view of child restraint systems in 30° frontal farside impact.

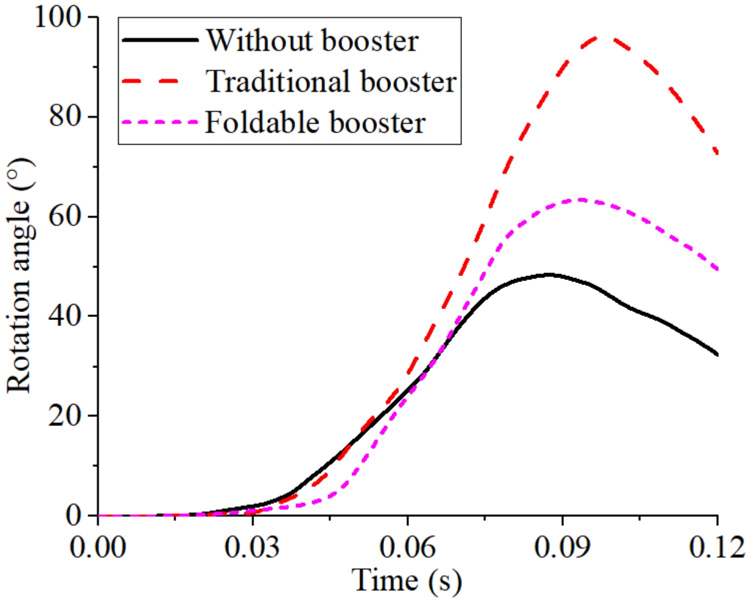


Fig. 43 Children's head acceleration in 30° frontal farside impact.

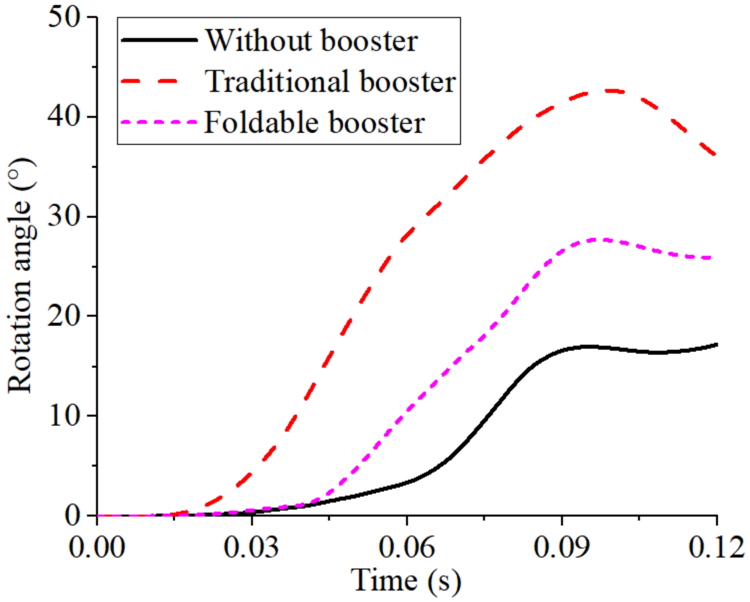


Fig. 44 Children's upper extremity rotation acceleration in 30° frontal farside impact.

Table 10. Summary of children's maximum rotation for 30° frontal far side impact loadcase.

	Traditional booster	Without booster	Foldable booster
Head rotation	48.4°	96.2°	63.4°
Percentage variations	0	98.8%	31.0%
Upper extremity rotation	17.2°	42.6°	27.7°
Percentage variations	0	147.7%	61.0%

3.3.4 Injuries in 30° frontal far side impact.

Fig. 33 and Fig. 34 illustrate the head and chest acceleration injury responses. The computed results show that the dummy's head acceleration, HIC_{15}, and chest acceleration with a foldable booster safety seat were 54.9g, 215.4, and 23.5g, giving a difference of 7.0%, 25.7%, and 1.7% compared to the case without the booster seat (51.3g, 171.4, and 23.1g). Furthermore, the traditional booster safety seat case (32.5g head acceleration, 267.1 HIC_{15}, and 15.1g chest acceleration) presented 36.6% lower head acceleration, 55.8% higher HIC_{15}, and 34.6% lower chest acceleration than those without using a booster safety seat. Table 11 summarizes the maximum injuries observed in 30° frontal far side impact scenarios.

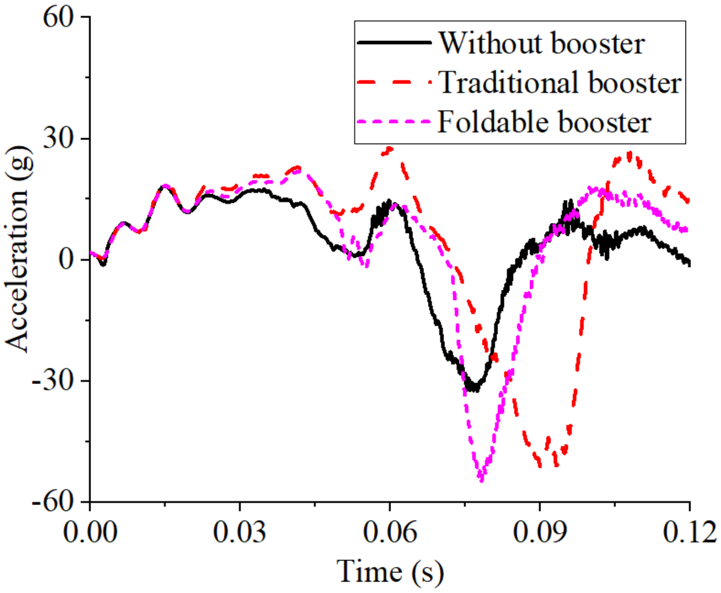


Fig. 33 Children's head acceleration in 30° frontal far side impact.

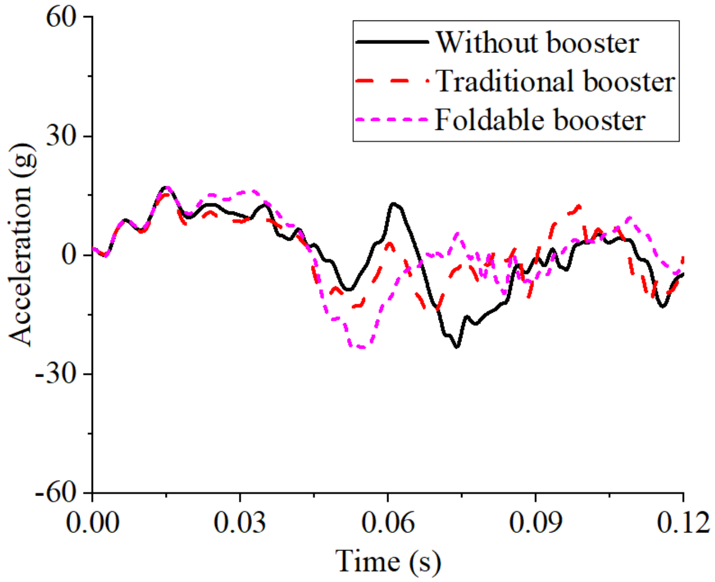


Fig. 34 Children's chest acceleration in 30° frontal far side impact.

Table 11. Summary of injuries for 30° frontal farside impact loadcase.

	Without booster	Traditional booster	Foldable booster	Accepted level (FMVSS 208)
Head acceleration	51.3g	32.5g	54.9g	--
Percentage variations	0	-36.6%	7.0%	--
HIC_{15}	171.4	267.1	215.4	700
Percentage variations	0	55.8%	25.7%	--
Chest acceleration	23.1g	15.1g	23.5g	60g
Percentage variations	0	-34.6%	1.7%	--

4 Discussion

It can be noted that the dummy with a traditional booster shows a lower risk of being strangled by a seatbelt in the frontal and far side impacts than the without a booster case. On the other hand, the dummy with a traditional booster seat shows a lower injury, including head acceleration and chest acceleration, than the dummy without a booster (three scenarios in five scenarios). Thus, the traditional booster could provide a safe situation for children passengers.

In the foldable booster case, the folded booster seat, which routes the seatbelt closer to the child dummy's shoulder, overall restraints the occupant better than in the scenarios without a booster and with a traditional booster. This can be observed in dummies' kinematics, where the vertical rotation is less for the foldable system. This can be explained by the fact that when the back seat belt and lap belt rotated (angles α and β, respectively) during the crash, they allowed the dummy to move forward, as shown in Fig.35.

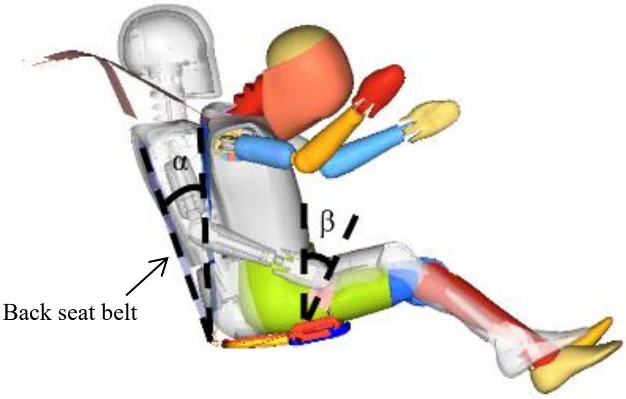
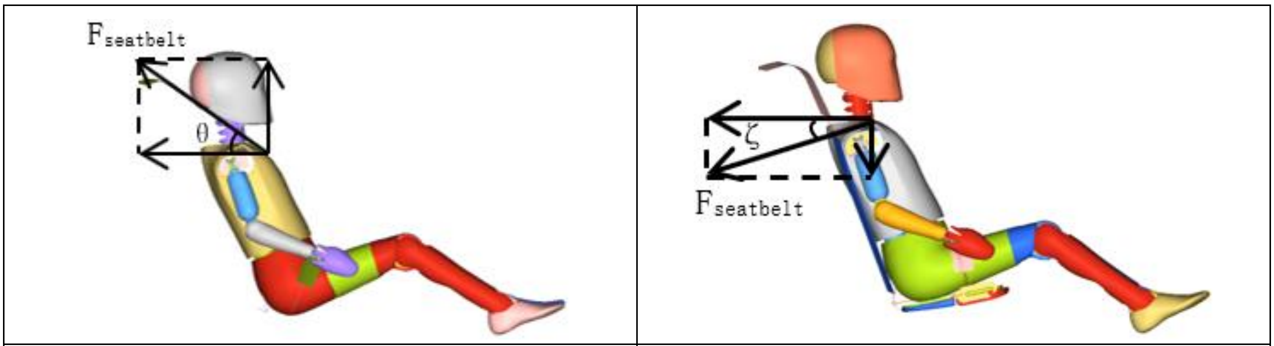


Fig. 35 Schematic diagram of back seat belt and lap belt corners.

As the foldable booster seat buckle lowers the height of the shoulder belt, it restricts the shoulder belt from sliding towards the dummy's neck during the impact, hence bringing two benefits to keeping children safe in a vehicle. First, the dummy using the foldable booster safety seat did not appear to be strangled by the entire shoulder belt and was better restrained in the seat. Thus, the foldable booster safety seat provides better child occupant protection for motor vehicle frontal crashes in kinematic subjects.

Secondly, the smaller contact area of the shoulder belt with the neck also resulted in pronounced higher head deflection in the dummy using the foldable booster safety seat. It can be seen that the head acceleration and HIC15 of the dummy using the foldable booster safety seat are higher than those of the dummy not using the booster safety seat and the dummy using the traditional booster safety seat. Nevertheless, this head acceleration and HIC15 are still very low and well within the safe legislative margin; hence should not cause significant risks to the occupant. This can be explained by the seatbelt geometrical angles between the shoulder belt, and the horizontal direction is reduced (angles ζ and θ, respectively), as shown in Fig. 36.



(a) Without a booster or with a traditional booster safety seat

(b) With foldable booster safety seat

Fig. 36 Analysis diagram of shoulder belt force.

The foldable booster seat case is subjected to a more significant horizontal component from the shoulder belt, resulting in higher chest acceleration than those without a booster seat and those using a traditional booster seat. Thus, the dummy using the foldable booster safety seat sustains higher chest accelerations in most cases, albeit still well within the safe safety margins. The study has demonstrated that booster seats keep the child in the seat, avoiding any head/body projection inside the vehicle, which is an undesirable scenario, like an unbelted case. This comes at the cost of increasing the forces slightly on the child's body. In the case studied, this extra force does not increase the injury severity experienced by the child. Consequently, the booster seats' restraining properties outweigh the slight force increase.

The results mentioned above indicated that all dummies in the three restraint systems did not exceed the limit for child occupant injury. Overall, if the injuries sustained by the foldable booster seat are higher than without using a booster seat and using a traditional booster safety seat, the increase of injuries is negligible and within the safety limits.

5 Conclusion

This paper illustrated the effectiveness of the foldable booster safety seat. The study has evidenced that scenarios with the foldable booster safety seat presented fewer risks of strangling a child than using no booster seat and a traditional booster seat, suggesting a certain safety improvement introduced and accepted by the population. It was, however, evidenced that the head acceleration, HIC_{15}, and chest acceleration of the dummy using the foldable booster safety seat is higher than those without using the foldable booster safety seat and those using the traditional booster safety seat because the child is better restrained in the seat; however, this increase is well within the safe targets set by legislation.

Acknowledgments

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