Applied Ergonomics 118 (2024) 104283

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Unlatching school bus seat belt buckles: Considerations for young passengers

Shivaprasad Nageswaran [a,*], Yousif Abulhassan [b], Jerry Davis [a], Richard Sesek [a], Mark Schall [a], Sean Gallagher [a]

[a] Department of Industrial & Systems Engineering, 3301, Shelby Center, Auburn University, AL, 36849, USA
[b] Department of Public Health, California State University, Sacramento, Solano Hall 4038, 6000 J Street, Sacramento, CA, 95819, USA

A R T I C L E I N F O

Keywords:
Seat belt
School bus
Rollover
Crashes
Surface transportation

A B S T R A C T

Automobile seat belts reduce the risk of injuries and fatalities resulting from a crash. As seat belts become more prevalent on large school buses, characterizing the capabilities of children to operate the unlatching mechanism of a seat belt is crucial to ensure the post-crash safety of young passengers. This study evaluated the strength capabilities of children and their abilities to unlatch a school bus seat belt when a school bus is in both the upright and rolled-over orientations. Push force exertions on a seat belt buckle push button were measured and compared to the seat belt assembly release force requirements specified in Federal Motor Vehicle Safety Standard (FMVSS) No. 209. Results of the study suggested that children do not have the strength to exert the maximum force of 133 N to release a seat belt assembly as specified in FMVSS No. 209; however, most children could unlatch a typical school bus seat belt assembly in the upright and rolled-over orientations.

1. Introduction

School buses are considered the safest mode of transportation for children between school and home (NSC, 2021). In the United States, approximately 470,000 school buses transport over 25 million children every day while traveling more than 9 billion kilometers (5.7 billion miles) annually (NCSL, 2022). Despite having an exceptional safety record, 13 school bus passenger fatalities occur annually (FARS, 2018). Approximately 50% of those fatalities resulted from school bus rollovers (FARS, 2018).

Large school buses with a gross vehicle weight rating (GVWR) greater than 4536 kg (10,000 pounds) rely on compartmentalization to protect passengers involved in a crash (NHTSA, 2011). In lieu of seat belts, compartmentalization requires seats to be closely spaced to one another and utilizes energy-absorbing seat backs to restrain passengers (NHTSA 2011; NHTSA, 2023). Compared to the restraint capabilities of seat belts, compartmentalization can effectively protect passengers in frontal and rear-end collisions; however, it may provide minimal to no protection for passengers in rollover crashes (Lapner et al., 2003).

Federal regulations related to motor vehicle safety are established by the National Highway Traffic Safety Administration (NHTSA) through a series of Federal Motor Vehicle Safety Standards (FMVSS). The design and protection requirements for school bus passengers are regulated by FMVSS No. 222 - School Bus Passenger Seating and Crash Protection (NHTSA, 2011). Occasionally, NHTSA has updated FMVSS standards to improve passenger safety based on recommendations made by the National Transportation Safety Board (NTSB). For instance, before 2011, school buses with a GVWR of less than or equal to 4536 kg (10,000 pounds) were only required to have lap belts. In 2008, NHTSA updated FMVSS No. 222 to require school buses with a GVWR of less than or equal to 4536 kg (10,000 pounds) manufactured after October 21, 2011, to have lap/shoulder seat belts (USDOT, 2011).

On November 21, 2016, a school bus driver was speeding while using a cell phone and ran off the road in Chattanooga, TN. The school bus, transporting 37 students, rolled over and crashed into a tree killing six children between the ages of 6–10. Additionally, six passengers were seriously injured, and 20 passengers received minor injuries (NTSB, 2018). Citing this crash, a special investigation published by the NTSB in 2018 recommended the enactment of legislation that would "require all new large school buses be equipped with passenger lap/shoulder belts for all passenger seating positions in accordance with Federal Motor Vehicle Safety Standard 222" (NTSB, 2018). Currently, Federal regulations do not require large school buses to have lap/shoulder seat belts for passengers but allow individual states to determine whether to require

* Corresponding author.
E-mail address: szn0043@auburn.edu (S. Nageswaran).

https://doi.org/10.1016/j.apergo.2024.104283
Received 29 September 2023; Received in revised form 6 February 2024; Accepted 2 April 2024
Available online 11 April 2024

seat belts on large school buses (NHTSA, 2011). Only eight states have standards requiring seat belts on school buses with a GVWR greater than 4536 kg (10,000 pounds) (NCSL, 2022). However, it is believed that more state and local jurisdictions may consider installing seat belts on school buses in response to the NTSB recommendations.

FMVSS 209 specifies the requirements of seat belt assemblies used in passenger vehicles, trucks, and buses (NHTSA, 2007). Buckle release force refers to the maximum force required to release a seat belt assembly. FMVSS No. 209 specifies that the buckle release force required to release the seat belt assembly of lap or lap and shoulder restraint systems should be less than 133 N. While FMVSS 209 requires the adjustment range of seat belt assemblies to accommodate the anthropometric range of those from a 5th percentile female to a 95th percentile male, it does not provide any guidance on whether the maximum allowable force of 133 N force for seat belt buckle operation is acceptable for individuals with lower strength capabilities such as young children.

Considering the strength capabilities of young children is necessary to determine if they can operate seat belt assemblies in post-crash scenarios. Published data on force exertion and strength capabilities of children are sparse. In a study published by the Department of Trade and Industry (DTI) in 2002, maximum thumb and finger force exertions of the dominant hand of six-to ten-year-old (6–10) children were recorded (DTI, 2002). The subject was either standing with a button (20 mm circular plate) at elbow height or seated with a button at the side of the hip (50 mm cube) at seat pan height. Small children were allowed to rest their feet on a box. The study reported a mean thumb push force of 71 N for females and 85 N for males: and a mean index finger push force of 42 N for females and 43 N for males on a 20 mm circular plate (Peebles and Norris, 2003). For the 50 mm cube, the study reported a mean thumb push force of 83 N for females and 67 N for males and a mean push force for using two or more fingers of 67 N for females and 56 N for males. Force exertion data published by Peebles and Norris suggest that the push exertion capabilities of six to ten (6–10) year old children may be less than what would be required to unlatch a seat belt buckle.

FMVSS 209 specifies that a seat belt buckle designed for push-button application shall have a minimum surface area of 452 mm^2. Additionally, United Nations Economic Commission for Europe (UNECE) Regulation 16 Standard 2.4.2.2 specifies that the minimum width of the buckle should not be less than 15 mm (UNECE, 2007). FMVSS 209 also states that the buckle release mechanism shall be designed to minimize the possibility of accidental release/inadvertent release. To comply with this standard, seat belt push buttons are often enclosed or shrouded. A typical school bus seat belt buckle is rectangular, has a minimum dimension of 15 mm × 31 mm, and is shrouded. The push force required to unlatch the seat belt assembly is usually exerted while the occupant is seated. It is currently unknown what strategies young children would employ when pushing the release push-button; fingers, thumb, or a combination of both. Due to these factors, the force exertion data from general strength studies may not accurately represent the force exertion capabilities of a seated passenger to unlatch a seat belt buckle (Abulhassan et al., 2018a; Peebles and Norris, 2003). The postures adopted in collecting force exertions and the geometric shapes of force application points from previous studies do not represent push force exerted on a seat belt buckle push button.

In a separate study on school bus safety, Abulhassan et al., 2018 measured the amount of force children in Kindergarten through second grade could exert on a school bus roof hatch knob. The purpose was to compare this force with the maximum permissible force required to unlatch a roof hatch. Like the force requirement specifications of FMVSS 209 for seat belts, FMVSS No. 217 requires the release mechanism on school bus roof hatches to operate with a force of 89 N or less (NHTSA, 2011b). The study suggested that school bus roof hatches did not consider the strength capabilities of children. Only 40% of Kindergarten children tested could exert a push force on the roof hatch greater than or equal to 89 N (Abulhassan et al., 2018b). In the US, Children are assigned into year groups known as grades. Most children enter the public education system around the age of five or six. Grades start at Pre-Kindergarten and increase to the twelfth grade (12).

Fire propagation studies suggest that the available time for successful evacuation from a school bus could be as little as 3–5 min (Matolcsy, 2010). Recently published school bus evacuation research studies have identified several concerns with the physical and cognitive abilities of young children to operate school bus emergency exits and successfully evacuate a school bus in a post-crash situation (Abulhassan et al., 2016, 2018a, 2018b; Gunter et al., 2020a, 2020b; Davis and Abulhassan, 2021). Adding seat belts that are inoperable by children could further increase evacuation times and reduce post-crash survivability rates.

The objectives of this study were to address concerns associated with unbuckling a school bus seat belt by determining if: (1) The push force that children can exert on a belt buckle push button is 133 N or more; (2) The force exertion on a seat belt buckle is the same when a child is seated in the upright and the 90° rolled-over orientation; and (3) Children can unlatch a typical school bus seat belt in the upright and 90° rolled-over orientation.

2. Methods

2.1. Subjects

A total of 53 subjects (35 females and 18 males) between the ages of 5 and 16 years old were recruited from a gymnastics camp at the Auburn Gymnastics Academy (AGA) facility in Auburn, AL (Table 1). This study was approved by the Institutional Review Board (IRB) at Auburn University. Approved letters of consent were distributed to the parents and guardians before the study. Parental consent and subject assent were obtained prior to participation in the study. For analysis, Pre-Kindergarten was coded as 1, Kindergarten as 2, and so on.

2.2. Equipment

A school bus seat rollover simulator was designed and fabricated to simulate a passenger fastened in a school bus seat when the bus is upright or in a 90° rolled-over orientation (Fig. 1). A Standard IMMI® Safeguard school bus bench seat equipped with adjustable seat belts on both sides was mounted on the custom-built apparatus. The AGA foam pit allowed subjects to fall safely from an elevation when successfully unlatching a seat belt assembly in the rolled-over orientation, as shown in Fig. 2. A Chatillon DFS2-R-ND Digital Force Dynamometer with the Chatillon SLC-0500 Remote Force Loadcell was used to measure the push force exertion on a custom push-button prototype that is geometrically identical to a school bus seat belt push button.

Table 1
Subject anthropometric and demographic information.

Variable	Sex	N	Mean	SD	Minimum	Median	Maximum
Age (years)	F	35	7.5	1.6	5.0	8.0	10.0
	M	18	8.3	2.3	5.0	8.5	12.0
Grade	F	35	3.9	1.7	1.0	4.0	7.0
	M	18	4.7	2.3	2.0	5.0	9.0
Weight (kg.)	F	35	24.7	5.4	17.2	24.9	35.4
	M	18	29.1	8.3	19.1	27.0	43.1
Height (cm.)	F	35	127.5	8.4	114.0	127.5	145.0
	M	18	134.6	9.4	118.1	134.6	153.9
BMI (Kg/m^2)	F	35	15.0	1.9	12.1	14.5	19.3
	M	18	15.8	3.1	11.4	14.7	23.3

Fig. 1. School bus seat rollover simulator.

2.3. Experimental setup

Two stations were set up for data collection. In the first station, subject demographic and anthropometric data were collected. Seat belt button push force exertion and unlatching capabilities were measured in the second station. The experiment was conducted in two phases. Phase 1 measured the force exertions at different orientations (0° and 90°), and Phase 2 measured the unlatching ability of the subjects. The primary reason for splitting the experiment into two phases was to swap the load cell according to the requirements of the study. The order of the phases was randomized.

The goal of the first phase was to measure the maximum push force exerted by an occupant in different orientations on a push-button buckle prototype. Seat belt unbuckling and push force exertion were only measured in the upright (0°) and 90° rolled-over orientations. In a school bus, seat belt buckles may be positioned on the passenger's left or right side, depending on whether they are seated closer to the aisle or the window (Fig. 1). Additionally, a passenger could unlatch the seat belt by pressing the push-button with either their thumb or by using multiple fingers. For this study, the number of fingers was not treated as different groups because depending on the anthropometry of an individual, he or she may be able to exert a push force with anywhere between one to four fingers on the push button. Push force exertion data were defined in two categories: using the thumb or using multiple fingers. Originating from these, eight force exertion trials were measured for each subject (Fig. 3). The order of force exertion trials for each subject was determined using a split-split-plot randomization technique.

When a subject was ready to participate in a trial, they were asked to sit on either the left or right side of the seat according to the randomized trial order and instructed to don the three-point seat belt. A research assistant adjusted the shoulder strap height adjuster to ensure a proper fit. The seat belt buckle was then covered to prevent accidental unlatching while the subject applied a push force exertion on the force dynamometer located near the seat belt buckle (see Fig. 2). For trials where push force exertion was collected in the rolled-over orientation, two research assistants tilted the simulator to a 90° angle after the subject was secured (Fig. 4).

Maximum voluntary contraction (MVC) methodologies used in similar studies were followed to measure maximum push force exertions (Abulhassan et al., 2018b; DTI, 2002; McDonald et al., 2017). Upon a signal from the research assistant, the subject was asked to exert a push force on the push button prototype and reach their maximum effort after 3 s. The subject was asked to hold the maximum effort for 3 s and slowly release the force over 3 s. Between each exertion trial that required the subject to use the same digits, a 2-min rest interval was implemented to reduce the effects of fatigue. After all the force exertion trials were conducted, the subject was returned to the upright orientation, the three-point harness was unlatched, and they stepped off the device. The subjects were asked to rest as the researchers removed the load cell setup for the study's second phase.

The study's second phase aimed to determine if the subject could unlatch the seat belt in the upright and rolled-over orientation. As described earlier, depending on whether a passenger is seated closer to the aisle or window, the seat belt buckle may present itself on either the left or right side of the passenger. In a post-crash or emergency scenario, the passenger could unlatch their seat belt using their fingers, thumb, or a combination. Therefore, the type and number of fingers used to unlatch the buckle was not studied in the study's second phase. Each subject participated in four seat belt unlatching trials: using the left hand in the upright and rolled-over orientations and using the right hand in

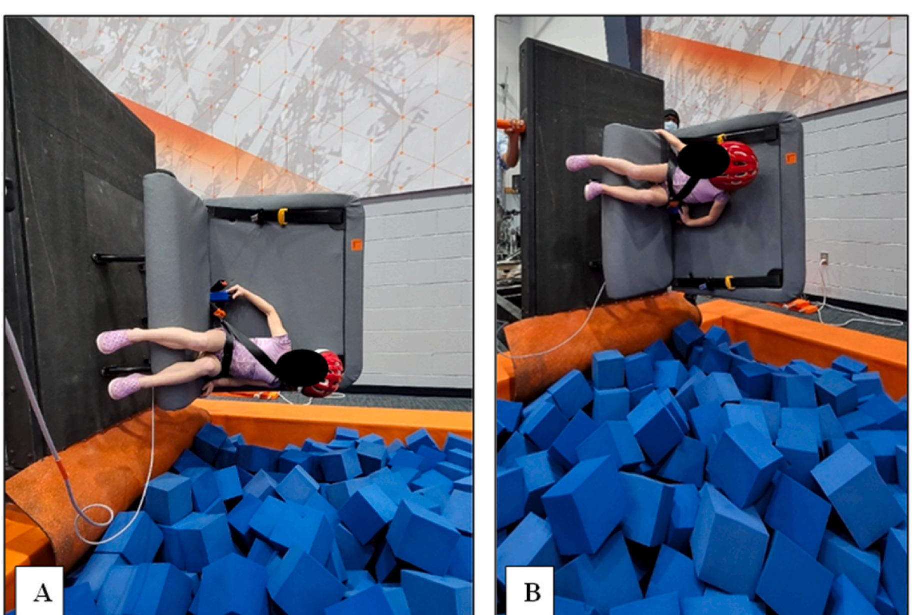

Fig. 2. Rollover simulation (A) seating position with buckle on the right side; (B) seating position with buckle on the left side.

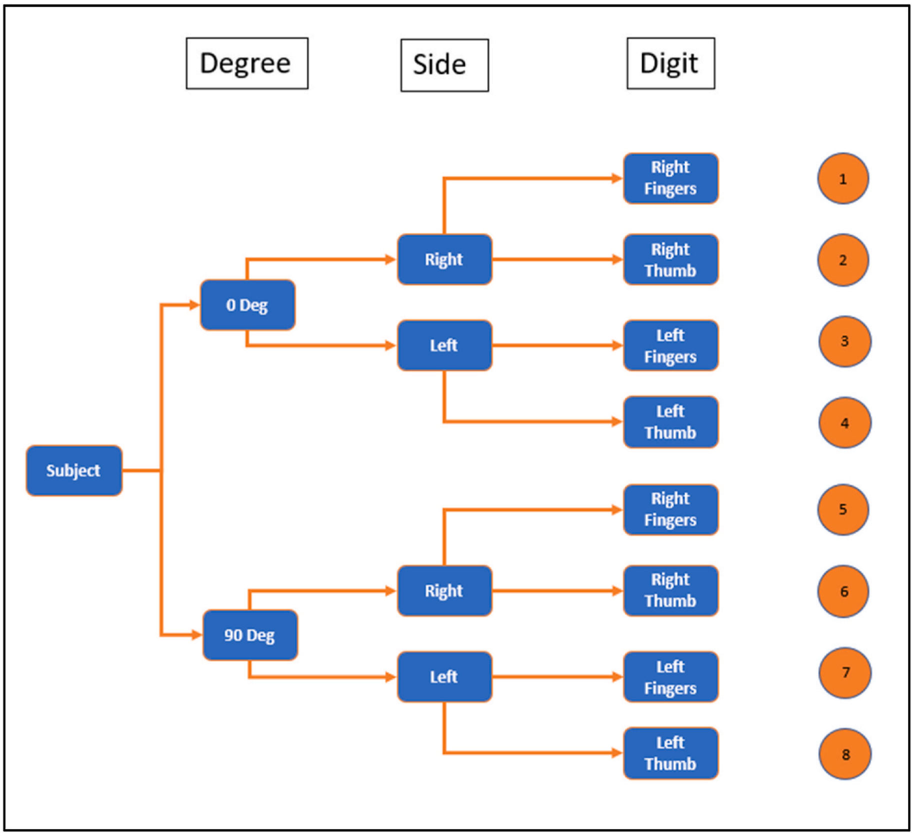

Fig. 3. Push force exertion trials.

Fig. 4. Push force exertion data collection setup.

the upright and rolled-over orientations. The order in which these unlatching trials were performed was randomized. When the subject was ready, they were asked to sit on the side of the seat according to the randomized trial order. The subject was then asked to don the three-point seat belt. The shoulder strap height was adjusted by a research assistant to ensure a proper fit. For trials conducted in the rolled-over orientation, subjects were asked to unlatch the seat belt buckle once the simulator was in the rolled-over orientation. For consistency in data collection, subjects were requested to unlatch only using the side of the hand coinciding with the location of the buckle. If the subject successfully unlatched, they safely fell into the foam pit (Fig. 5). Once the subject exited the foam pit and was at a safe distance, the device was lowered, and the next trial was conducted. For trials conducted in the upright orientation, the subject was asked to unlatch the buckle upon receiving a signal from the research assistant. Once it was observed that the buckle was unlatched, they were asked to stand up and move to the next position to be tested. Subjects were given three attempts to unlatch the seat belt buckle. Each attempt was defined by the subject reaching

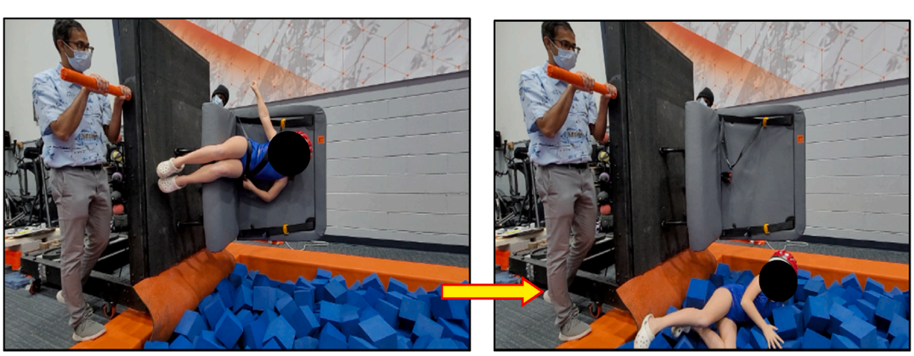

Fig. 5. Screen captures of seat belt unlatching in a rolled-over orientation.

the push button to unlatch and, if unsuccessful, taking their hand away from the button for the research assistant to see and proceed to the next attempt. Subjects could also ask to stop the experiment anytime if they felt uncomfortable or could not unlatch the buckle.

2.4. Statistical analysis

The categorical independent variables were sex, orientation (upright, 90° rollover), side of the hand used (right, left), and digit/s used (thumb, multiple fingers); continuous independent variables included body mass index (BMI), age, and grade. The dependent variables measured in this study were the force exertion in the upright and rolled-over orientations and the ability to unlatch the seat belt buckle in the upright and rolled-over orientations. Force exertion data were tested for normality using Ryan-Joiner normality tests. A one-sample *t*-test was performed at each orientation to determine if the maximum push force exerted by subjects was greater than the standard specified maximum buckle release force of 133 N. Due to multiple tests, a new significance level of 0.00625 was determined instead of the conventional 0.05 level for each individual *t*-test using the Bonferroni Correction method. An analysis of variance (ANOVA) following a split-split-plot factorial design for each sex was conducted to study the statistical significance of subject orientation on force exertion. A regression was performed to study the effects of age, grade, BMI, sex, side, digit, and orientation on force exertions. For analysis, Pre-Kindergarten was coded as 1, Kindergarten as 2, and so on for other grades. The backward elimination method ($\alpha = 0.05$) was implemented to determine the variables that best describe the force exertion data. A binary logistic regression with stepwise elimination to determine the best-fitting model was used to identify if the study's independent variables had a statistically significant effect on the unlatching ability of the subjects. Statistical analyses were performed in Minitab 21 (2023), State College, PA, USA: Minitab Inc., SPSS (2023 IBM SPSS Statistics 29, Chicago, IL, USA), and StatistiX 9.0 (Analytical Software; Tallahassee, FL, Maryland, USA).

3. Results

3.1. Descriptive statistics

Among the 53 recruited subjects, three males and two females elected to withdraw from the study following the initial demographic and/or anthropometric data collection or after the preparatory phase of data collection. Forty-eight (48) subjects (33 females and 15 males) completed the study, and their data were included for analysis. Table 2 presents the descriptive statistics for the force exertion tests. Fig. 6 illustrates this data graphically. **There were eight occasions where an individual could not unlatch their seat belt**. Three females and three males could not unlatch the seat belt buckle in at least one condition in the 90° rolled-over orientation. Table 3 presents the demographic and anthropometric data of the subjects who **could not unlatch the seat belt**.

3.2. Inferential statistics

The results of Ryan-Joiner normality tests indicate that the force exertions data at each orientation trial were not significantly different from a normal distribution ($\alpha = 0.05$, RJ > 0.95). One sample t-tests (H_0: $\mu \geq 133$ N) performed on each of the eight test configurations suggest that the mean push force exerted on the seat belt buckle push button is significantly less than 133 N ($p < 0.00625$ for all eight test configurations). Results of the split-split-plot factorial design ANOVA suggest that subject orientation, location of the seat belt or the side of the hand, and digit used to apply the push force had statistically significant effects on push force exertion (all $p < 0.05$). The partial eta-squared values for these effects were higher than 0.14, indicating that the magnitude of these effects was statistically large. Tukey honest significant difference (HSD) posthoc tests suggested that a significant difference existed between the mean push force exertions in the upright and rolled-over orientations ($p < 0.05$)

According to the partial eta-squared values, the largest effect size ($\eta^2 = 0.20$) is associated with the digit, followed by orientation ($\eta^2 = 0.10$. Most of the variables in the ANCOVA table had small effect sizes, with partial eta-squared (η2) values around 0.01.

As outlined in Table 3, the subjects could not unlatch the seat belt in eight (8) of the 184 seat belt unlatching trials. Results of the binary logistic regression with stepwise elimination to determine the best fitting model for the independent variables suggested that grade was the only independent variable to have a statistically significant effect on the ability to unlatch the seat belt ($p = 0.006$, 95% CI [1.3, 5.7]).

4. Discussion

Results of this study suggest that while most of the subjects (>95%) were able to unlatch a seat belt in the 90° rolled-over orientation, none of the subjects were able to meet the maximum force allowed by seat belt manufacturers to operate and unlatch a seat belt as defined in FMVSS No. 209. **None of the subjects recruited in this study exerted a 133 N push force on a seat belt buckle in any orientation or testing configuration.** The mismatch between the strength capabilities of children and seat belt specifications defined by FMVSS No. 209 could be a major concern as seat belt-equipped school buses could potentially have different seat belt specifications that meet the requirements of FMVSS No. 209 but pose a danger to children in post-crash scenarios.

Amending FMVSS No. 209 to define distinct requirements for

Table 2
Seat belt buckle push force exertions (N).

Orientation & Buckle Location	Digit	Code	Sex	n	Mean	SD	Min	Max
Upright	Thumb	0LT	F	33	45.5	18.0	10.2	82.2
Left Buckle			M	15	54.7	19.3	25.0	83.0
Upright	Multiple	0LF	F	33	40.7	15.3	11.2	66.0
Left Buckle	Fingers		M	15	44.4	15.3	18.6	78.2
Upright	Thumb	0RT	F	33	48.0	17.5	13.8	88.4
Right Buckle			M	15	60.0	23.0	11.8	88.8
Upright	Multiple	0RF	F	33	41.3	14.6	12.6	70.6
Right Buckle	Fingers		M	15	47.2	18.6	13.6	78.8
90° Rollover	Thumb	90LT	F	33	40.3	17.8	12.4	82.4
Left Buckle			M	15	47.0	23.2	11.6	91.6
90° Rollover	Multiple	90LF	F	33	36.9	17.0	10.4	73.2
Left Buckle	Fingers		M	15	38.3	21.7	10.2	79.0
90° Rollover	Thumb	90RT	F	33	39.9	15.8	11.6	77.4
Right Buckle			M	15	54.4	20.3	27.2	94.0
90° Rollover	Multiple	90RF	F	33	34.3	13.4	10.2	58.2
Right Buckle	Fingers		M	15	46.9	17.8	17.4	78.2

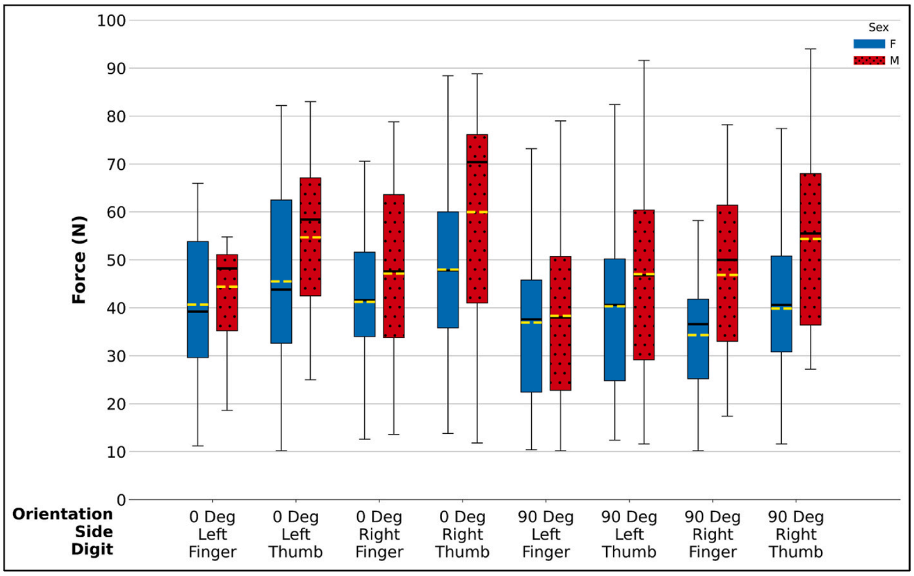

Fig. 6. Boxplot of Force (N) Exerted at Each Orientation. The Boxplot illustrates the distribution of force data, with the box representing the interquartile range (IQR), the black straight line inside the box indicating the median, and the dashed yellow line highlighting the mean. The whiskers extend to the minimum and maximum values within 1.5 times the IQR, depicting the central tendency and spread of the dataset. represents the data for female subjects and represents the data for female subjects. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Summary of subjects **unable to unlatch seat belt buckle** in the 90° rollover orientation.

Sex	Age	Grade Level	BMI	Buckle Location
F	5	Kindergarten	12.6	Left and Right Side
F	5	Pre-K	18.6	Left Side
F	5	Pre-K	13.0	Right Side
M	6	Kindergarten	13.8	Right Side
M	7	1st Grade	14.8	Left Side
M	7	1st Grade	23.3	Left and Right Side

maximum allowable force for the operation of school bus seat belt buckles could address the concerns associated with the lower strength capabilities of school bus passengers compared to adults. The results of this study identified a statistically significant difference in push force exertions when a subject was in the upright orientation versus the 90° rolled-over orientation. Additionally, all observations of data collection trials where a subject could not unlatch the seat belt occurred when the subject was in a 90° rolled-over orientation. These findings suggest that post-crash orientations can significantly impact the ability of a passenger to unlatch a seat belt and should be considered in the development of school bus seat belt standards.

This study focused on scenarios where immediate egress is imminent. However, there are risks associated with children unlatching themselves after a crash especially if a school bus is rolled over. A child on the higher side of the vehicle could potentially fall the entire width of the bus and sustain an injury or injure other occupants. The safety consequences of children being unable to release a seat belt buckle in a rollover condition should be further investigated.

5. Limitations

This study aimed to address several gaps in the existing literature on the capabilities of children to operate school bus seat belts. It provides valuable insight into the force exertion capabilities of children and their ability to unlatch a seat belt. However, there are several limitations associated with this study. The sample size of this study is comparable to other published school bus safety studies that measured the strength capabilities of children. However, the sample was relatively small and may not be generalizable to the entire population of school bus passengers. Subjects in this study were recruited from one area (Auburn, Alabama). A broader sample size with equal representation of different BMI groups, ages, and grade levels could provide a better understanding of how these factors affect the force exertion of subjects and their ability to unlatch, especially in a rolled-over orientation.

The tests were conducted in only one rollover orientation (90°) for both the unlatching and force exertion phase. Only one seat and seat belt system from a single manufacturer was tested. Additionally, a feedback system was not installed, encouraging the children to push harder. These constraints further limit the generalizability of our results.

Another limitation of the study was the sample selection. Subjects were recruited from a gymnastics camp. The sample may increase the likelihood of selection bias as these individuals may have developed enhanced physical abilities compared to subjects not exposed to such physical training. The strength capabilities of this group may be higher than the general population. Due to scheduling limitations, the maximum push force exertion was measured only once per subject. Additional trials may have resulted in different force exertion results. It is also acknowledged that post-crash scenarios like smoke, fire, darkness, injuries, fear, or other environmental stressors could generate different results. A child's strength in a crash situation could be substantially different due to adrenaline (potential increase) or shock (potential decrease). Despite these limitations, after an extensive literature search, it is believed that this is the sole study to measure seat belt buckle push force exertion and children's abilities to unlatch a seat belt in a rolled-over orientation. The results of this study could serve as a valuable framework for future transportation safety studies.

6. Conclusions

All subjects except six unlatched the school bus seat belt while in a rolled-over orientation. However, none of the subjects could exert a force exceeding the 133 N maximum required to release a seat belt assembly specified by FMVSS No. 209 at any given orientation. The mean maximum force exerted by subjects at upright orientation was 45% of the maximum force required to release a seat belt assembly (133 N) for males and 36% for females. For male subjects, a reduction of almost 10% in the mean push force from an upright to a rolled-over orientation was observed. For female subjects, a reduction of almost 14% in the mean push force from an upright to a rolled-over orientation was observed. The mean push force for female subjects was 83% of that for male subjects.

Research has shown that in a rollover crash, seat belt webbing tension increases, thereby increasing the buckle release force (Davee et al., 2008; Moffatt et al., 1995; Hare et al., 2002; Kumaresan et al., 2006; McCoy and Chou, 2007). Additional research is warranted to study different unlatching methods and potentially develop a seat belt release mechanism independent of the belt tension. Seat belts are highly effective in reducing deaths and injuries in motor vehicle collisions. Research has also shown that seat belt laws effectively increase seat belt usage (Cohen and Einav, 2003; Dinh-Zarr et al., 2001). With more communities and lawmakers considering mandatory seat belt policies for school buses, it is reasonable to hypothesize that seat belt usage among children on buses will also increase. Therefore, it is crucial to carefully consider the potential impact of seat belts on child safety and to ensure that any new regulations are designed to provide maximum protection.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was supported by the Deep South Center for Occupational Safety and Health (Grant # 2T42OH008436 from NIOSH) through the Pilot Project Research Training Program. Its contents are solely the authors' responsibility and do not necessarily represent the official views of NIOSH. Gratitude is expressed to Mr. Kurt Hettinger, assistant coach, Auburn University Gymnastics, for his assistance; the Auburn Gymnastics Academy for providing the facility to conduct the experiments; Dr. Alan Gunter for his expertise and assistance in the fabrication of the test device; and Mr. Don Ingram, Transportation Coordinator at Auburn City Schools, Auburn, Alabama, for providing school bus seats for the study.

References

Abulhassan, Y., Davis, J., Sesek, R., Gallagher, S., Schall, M., 2016. Establishing school bus baseline emergency evacuation times for elementary school students. Saf. Sci. 89, 249–255.

Abulhassan, Y., Davis, J., Sesek, R., Callender, A., Schall, M., Gallagher, S., 2018a. Physical and cognitive capabilities of children during operation and evacuation of a school bus emergency roof hatch. Saf. Sci. 110, 265–272.

Abulhassan, Y., Davis, J., Sesek, R., Callender, A., Schall, M., Gallagher, S., 2018b. Evacuating a rolled-over school bus: Considerations for young evacuees. Saf. Sci. 108, 203–208.

Cohen, A., Einav, L., 2003. The effects of mandatory seat belt laws on driving behavior and traffic fatalities. Rev. Econ. Stat. 85 (4), 828–843.

Department of Trade and Industry (DTI), 2002. "Strength Data for Design Safety-phase 2," Product Safety and Testing Group. Institute for Occupational Ergonomics and Division of Manufacturing, Nottingham, England, 2002.

Davee, D., Raasch, C., Moralde, M., Van Arsdell, W.W., 2008. Seat belt buckle release by inadvertent contact. SAE World Congress & Exhibition 2008, 1–1236.

Davis, G.A., Abulhassan, Y., 2021. Establishing the basis for a school bus emergency evacuation time standard. Transp. Res. Interdiscip. Perspect. 10, 100389.

Dinh-Zarr, T.B., Sleet, D.A., Shults, R.A., Zaza, S., Elder, R.W., Nichols, J.L., Task Force on Community Preventive Services, 2001. Reviews of evidence regarding interventions to increase the use of safety belts. Am. J. Prev. Med. 21 (4), 48–65.

FARS, 2018. Fatality Analysis Reporting System (FARS): 2004-2017 Final File and 2018 Annual Report File (ARF).

Gunter, L., Davis, J., Abulhassan, Y., Sesek, R., Gallagher, S., Schall, M., 2020a. School bus rear emergency door design improvements to increase evacuation flow. Saf. Sci. 121, 64–70.

Gunter, L., Davis, J., Abulhassan, Y., Sesek, R., Schall, M., Gallagher, S., 2020. Increasing evacuation flow through school bus emergency roof hatches. Appl. Ergon. 88, 103178.

Hare, B.M., Lewis, L.K., Hughes, R.J., Ishikawa, Y., Iwasaki, K., Tsukaguchi, K., 2002. Analysis of rollover restraint performance with and without seat belt pretensioner at vehicle trip. SAE Trans. 1382–1396.

Kumaresan, S., Sances, A., Carlin, F., Frieder, R., Friedman, K., Renfroe, D., 2006. Biomechanics of side impact injuries: evaluation of seat belt restraint system, occupant kinematics and injury potential. August. In: 2006 International Conference of the IEEE Engineering in Medicine and Biology Society, pp. 87–90. IEEE.

Lapner, P.C., Nguyen, D., Letts, M., 2003. Analysis of a school bus collision: mechanism of injury in the unrestrained child. Can. J. Surg. 46 (4), 269–272. PMID: 12930103; PMCID: PMC3211644.

Matolcsy, M., 2010. New requirements to the emergency exits of buses. Sci. Soc. Mech. Eng (09-0181).

McCoy, R.W., Chou, C.C., 2007. A study of kinematics of occupants restrained with seat belt systems in component rollover tests. SAE Trans. 534–558.

McDonald, A.C., Sonne, M.W., Keir, P.J., 2017. Optimized maximum voluntary exertion protocol for normalizing shoulder muscle activity. International Biomechanics 4 (1), 9–16.

Moffatt, E.A., Thomas, T.M., Cooper, E.R., 1995. Safety Belt Buckle Inertial Responses in Laboratory and Crash Tests. SAE transactions, pp. 1634–1650.

NCSL, 2022. School bus safety. National Conference of State Legislators. https://www.ncsl.org/transportation/school-bus-safety.

NHTSA, 2007. 49 CFR, Part 571, (FMVSS). §571.209, Standard No. 209, Seat belt assemblies. USDOT. National Archives and Records Administration. Washington, DC.

NHTSA, 2011. 49 CFR, Part 571, (FMVSS). §571.222, Standard No. 222, School bus passenger seating and crash protection. USDOT. National Archives and Records Administration. Washington, DC.

NHTSA, 2011b. CFR. Part 571, federal motor vehicle safety standards (FMVSS), subsection 571.217, FMVSS No. 217, bus emergency exits and window retention and release. In: US DOT. Office of the Federal Register, National Archives and Records Administration. Washington, DC.

NHTSA, 2023. School bus safety. https://www.nhtsa.gov/road-safety/school-bus-safety.

NSC, 2021. Buses Safest Transportation for School Children. National Safety Council. https://www.nsc.org/community-safety/safety-topics/school-safety/buses-safest-transportation-for-school-children.

NTSB, 2018. National transportation safety board. In: "Special Investigation Report: Selective Issues in School Bus Transportation Safety: Crashes in Baltimore, Maryland, and Chattanooga, Tennessee," NTSBSIR-1802 PB2018-100932. May 2018, [Online]. Available: https://www.ntsb.gov/investigations/AccidentReports/Reports/SIR1802.pdf.

Peebles, L., Norris, B., 2003. Filling 'gaps' in strength data for design. Appl. Ergon. 34 (1), 73–88.

UNECE, 2007. Regulation No 16 of the Economic Commission for Europe of the United Nations (UN/ECE) — uniform provisions concerning the approval of: I. safety-belts, restraint systems, child restraint systems and Isofix child restraint systems for occupants of power driven vehicles II. vehicles equipped with safety-belts, restraint systems, child restraint systems and Isofix child restraint systems (OJ L 313 30.11.2007, p. 58, ELI. http://data.europa.eu/eli/reg/2007/16(2)/oj.

USDOT, 2011. Laboratory Test Procedure for FMVSS 222 School Bus Passenger Seating and Crash Protection. U.S Department of Transportation. https://www.nhtsa.gov/document/tp-222-05pdf.