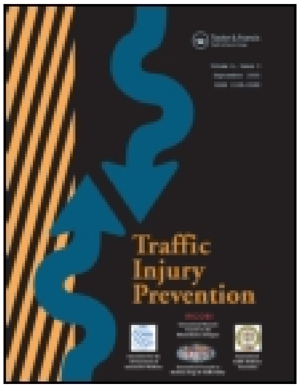

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Rear Seat Restraint System Optimization for Older Children in Frontal Crashes

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Objective: Analyses of crash injury data have shown that injury risk increases when children transition from belt-positioning boosters to the vehicle seat belt alone. The objective of this study is to investigate how to improve the restraint environment for these children.

Methods: A parametric analysis was conducted to investigate the effects of body size, seat belt anchorage locations, and rear seat design parameters on the injury risks in frontal crashes of children aged 6 to 12 years old using a newly developed parametric child anthropomorphic test dummy (ATD) model. Restraint design optimizations were also conducted to obtain ranges of optimal restraint system configurations that provide best protections for 6-, 9-, and 12-year-old children.

Results: Simulation results showed that child body size was the dominant factor affecting outcome measures. In general, lower and more rearward D-rings (upper belt anchorages), higher and more forward lap belt anchorages, and shorter, stiffer, and thinner seat cushions were associated with improved restraint performance. In these simulations, children with smaller body sizes require more-forward D-rings, inboard anchors, and outboard anchor locations to avoid submarining. However, these anchorage locations increase head excursions relative to more-rearward anchorages.

Conclusions: The balance of reducing head and knee excursions and preventing submarining indicates that an optimization approach is necessary to improve protection for 6- to 12-year-old child occupants. The findings of this study provided design guidelines for future rear seat restraint system.

Supplemental materials are available for this article. Go to the publisher's online edition of *Traffic Injury Prevention* to view the supplemental file.

Keywords: child passenger safety, restraint system optimization, rear seat, computer modeling, parametric child ATD model

Introduction

The number of U.S. children using belt-positioning booster seats in vehicles continues to grow as 47 states now mandate their use. However, compliance with these laws remains incomplete, and a substantial number of children who are too small to achieve good belt fit still travel without a booster or harness restraint. The latest recommendations from the National Highway Traffic Safety Administration (NHTSA 2011) and the American Academy of Pediatrics (2011) recommend booster use once a child outgrows the harness restraint (typically between ages 4 and 7) and booster use until the seat belt fits properly (typically between ages 8 and 12). However, caregivers relying on age-based guidelines in legislation are likely to transition their children out of boosters at or around age 8. These use patterns indicate a need for rear seating environments to provide good crash protection for children ages 8 to 12 who are not using boosters. The increased rate of injury when children transition from boosters to the vehicle seat belt alone also supports the need for improved crash protection for rear seat occupants (Arbogast, Jermakian, et al. 2009; Durbin et al. 2003; Winston et al. 2000).

When 6- to 12-year-old children use the vehicle seat belt without a booster, the vehicle seat and seat belt geometry affect restraint performance. Most rear seats are too long for children between ages 6 and 12 to sit without slouching (Huang and Reed 2006), and these children generally obtain poor lap and shoulder belt fit when seated without boosters (Reed, Ebert, et al. 2009). A poor lap belt fit (too high on the abdomen) allows the lap belt to deform the abdomen in frontal crashes through an occupant motion pattern known as *submarining*, potentially producing serious abdomen and spine injuries (Anderson et al. 1991; Arbogast et al. 2004, 2007; Santschi et al. 2005; Tso et al. 1993). Shoulder belts that fit too close to the child's neck can lead to the child putting the shoulder belt behind the back or under the arm (Garcia-Espana and Durbin 2008), and belts that are routed too far outboard can be ineffective in restraining the torso. Both of these types of misuse lead to poor torso restraint and an increased potential for head injuries due to contact with the vehicle interior.

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Previous experimental studies have demonstrated the effects of restraint conditions on the occupant responses in frontal crashes using Hybrid III (HIII) 6- and 10-year-old anthropomorphic test dummies (ATDs; Klinich et al. 2008, 2010). However, these tests were conducted using the Federal Motor Vehicle Safety Standard (FMVSS) No. 213 test bench, which has been reported to be longer, flatter, and softer than real vehicle seats (Reed 2011). More recently, a series of 13 sled tests was performed to evaluate the effects of seat cushion length and lap belt angle on child ATD kinematics in real vehicle seats using the HIII 6- and 10-year-old ATDs (Klinich et al. 2011). These test data provide valuable information for understanding the kinematics of child passengers with a range of sizes under different restraint configurations.

Computer simulation plays an increasingly important role in automotive safety research due to its cost-effectiveness relative to physical testing and its versatility in addressing a wide range of crash conditions. Previous studies using child ATD models have demonstrated the feasibility and usefulness of improving pediatric restraint system designs using computational modeling (Emam et al. 2005; Johansson et al. 2009; Menon et al. 2007). More recently, Hu et al. (2012) developed a modified HIII 6-year-old ATD model that incorporates new, more anatomically accurate ATD pelvis and abdomen designs. The modified ATD model correctly simulated ATD kinematics in cases with or without submarining under FMVSS No. 213 test conditions. However, because the physical versions of the modified pelvis and abdomen are still under development, they do not represent the performance of the standard HIII 6-year-old used in regulatory testing. Furthermore, the FMVSS No. 213 test bench was generally used to conduct parametric studies; a systematic optimization study focused on the design of belt restraints for children in real vehicle seats has not yet appeared in the literature. To solve this problem, Wu et al. (2012) developed a parametric child ATD model representing children from 6 to 12 years old. This ATD model along with a real vehicle seat model were validated against the sled tests conducted by Klinich et al. (2011) with the 6- and 10-year-old HIII ATDs over a range of belt and seat conditions. This model provides a valuable tool for future restraint system design optimization for children.

The present study aimed to develop design guidelines to improve crash protection for children seated in rear seats who are smaller than most adults yet unlikely to be using booster seats. An optimization study was performed using the parametric child ATD model developed by Wu et al. (2012), capable of representing the body sizes of children from ages 6 to 12 seated on a realistic second-row vehicle seat.

Methods

Method Overview

Custom software was developed to provide a highly automated system for conducting simulations within an optimization framework. The overall approach incorporates databases of child and restraint attributes, a computer program for setting up the model, crash simulations under different restraint conditions, and design improvement using optimization. A flowchart of the overall methodology for optimizing the restraint systems for older child passenger is shown in Figure A1 (see online Appendix). Child anthropometric databases and child seating posture data were used to create accurate child dimensions and posture. Belt anchorage locations and seat geometry obtained from vehicle measurements provided details of the seating environment. A custom computer program automated the process of scaling a generic seat model to the desired specifications, positioning the belt anchorages, scaling the ATD model to the desired body size, placing the ATD model on the seat in a realistic posture, and routing the belt in the same way a child would. Crash simulations were then conducted using a selected crash pulse. The outputs of the simulation included head and knee excursions; torso rotation; head, chest, and pelvis accelerations; and other injury measurements, such as the head injury criterion (HIC). The program was designed to run automatically, so that the seat and belt geometry can be optimized to reduce the risk of injury.

Parametric Child ATD Models Representing 6-to 12-Year-Old Children

In this study, a parametric child ATD MADYMO model previously developed by Wu et al. (2012) was used to conduct all simulations. This model can represent 6- to 12-year-old children and has been calibrated and validated against 12 sled tests with standard 6- and 10-year-old HIII child ATDs, 2 cushion lengths with realistic vehicle seats, and 3 seat belt locations (Klinich et al. 2011). The baseline version of this parametric model is shown in Figure A2A (see online Appendix). The standard abdomen and pelvis geometry of the original MADYMO 6-year-old child ATD model was refined by adding more detailed ellipsoids and facet meshes. To scale the baseline child ATD model into different body sizes, custom software was developed by combining MADYMO Scaler and a program written by Scilab V5.2.2 (Scilab Enterprises, France). The scaling was based on the anthropometric data of children from 2 to 12 years old available in the GEBOD (GEnerator of BODY data) database (Cheng et al. 1996), which was derived from the study by Snyder et al. (1977). The resulting models represent the average child attributes for children of each age. The height and weight information for ATDs at different ages used in the current study is shown in Figure A2B (see online Appendix).

Automated Computer Program for Setting Up Crash Simulations

An automated computer program was developed using a combination of MADYMO (TASS, The Netherlands), Scilab, and ModeFRONTIER (ESTECO, Italy) to integrate the parametric child ATD model, ATD positioning procedure, automatic belt fitting algorithm, and other crash conditions together.

A second-row captain's chair model from a 2008 Dodge Caravan was used in this study. Figure A3 (see online Appendix) shows the comparison between the underside of the real seat cushion and the seat cushion model. Facet elements constructed from scan data were used to obtain accurate geometry for the foam surface of the seat cushion. The supporting structures underlying the cushion were modeled by 2 cylinders. The front column was used to represent the steel frame at the front edge of the cushion, and the rear column was used to represent the 2 steel bars and the elastic webbing under the cushion foam. The contact characteristics of the seat cushion and the rear column of the seat structure were calibrated against data from 12 sled tests (Klinich et al. 2011; Wu et al. 2012), and the front column of the seat structure was defined as rigid.

The ATD position and seating posture were determined by the ATD stature and seat cushion length using a regression model developed by Reed et al. (2011). This seating posture model is based on child volunteer tests in realistic vehicle seating environments, thus providing a better representation of children's slouching posture caused by the relatively long seat cushion compared to their short thigh lengths. In the current study, the hip and head center of gravity (CG) points were used as the reference points to position the ATD.

An automated belt-fitting algorithm was developed by combining Scilab programs and a MADYMO belt-fit presimulation based on specific seat belt anchorage locations and the ATD size, position, and posture. The series of events in the automated belt-fitting algorithm were as follows:

1. The parametric child ATD model was scaled to a specific stature and weight and imported into the simulation environment. The hip and head CG points were placed to the locations predicted by the child seating posture model. All joints of the ATD were temporarily locked to ensure that no movement could occur for any body part during the belt-fitting, and all contact characteristics of the ATD were temporarily nullified to exhibit a rigid ATD surface.
2. Finite element (FE) seat belt segments, whose length can be adjusted according to the ATD stature, were input to the simulation environment. The position and length of the FE belts were varied according to the stature of the ATD. Multibody belts were used to connect the end of FE belts and 3 seat belt anchorages, whose positions were defined by specific simulation conditions. Belt retractors were modeled at the 3 anchorage points. The contact characteristics between the ATD and seat belt were based on a previous study by Wu et al. (2012), in which the contact characteristics were optimized based on data from 12 sled tests with 6- and 10-year-old HIII child ATDs under different restraint configurations.
3. A MADYMO presimulation was then executed. A 200 N force was applied to the 3 belt anchorages along the seat belt to remove the clearance between the seat belt and the ATD until the seat belt came in contact with the rigid child ATD. The total duration of the simulation was determined such that a proper belt fit was achieved for full ranges of anchorage locations and ATD sizes.
4. The final node coordinates of the belt elements were extracted from the belt-fitting presimulation results and input to the model for crash simulations.

Examples of ATD models positioned in a real vehicle seat generated by the automated computer program are shown in Figure 1. Note that the ATD model did not necessarily contact the seat back, because the ATD positioning procedure optimally located the hip joints and head CG according to the statistical model of child posture. The discrepancy between child and ATD posture in the torso arose because the ATD cannot slouch the way children do. The crash pulse, as shown in Figure A4 (see online Appendix), which is similar to the pulse associated with FMVSS 213 testing, was generated by averaging the pulses from the 12 sled tests used to tune and validate the model (Klinich et al. 2011).

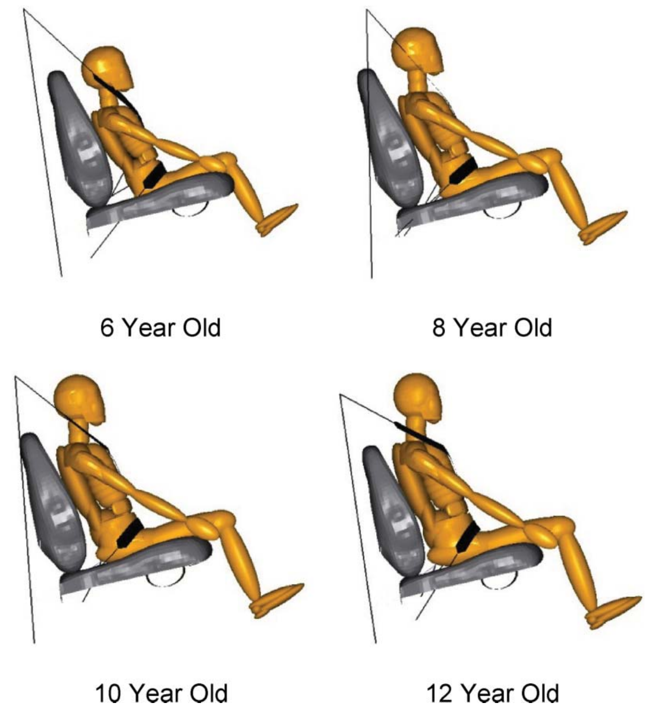

Fig. 1. Seating postures of dummies with different body sizes in a real vehicle seat: (a) 6-year-old; (b) 8-year-old; (c) 10-year-old; and (d) 12-year-old (color figure available online).

Parametric Study on Restraint System Design Factors

Given the wide range of ATD body sizes, positions, and postures; seat belt anchorage locations; and seat designs, a parametric study was performed to study the relationship between the various input parameters and a set of kinematic output variables representing the injury risks of child passengers in frontal crashes. A total of 1000 simulations were performed with the input parameters sampled using the uniform Latin hypercube method. The input parameters included ATD body size (represented by age), 3D locations of the 3 seat belt anchorages, seat cushion length and stiffness, and seat supporting structure vertical location. Key output variables considered in the parametric study were maximal head excursion, maximal knee excursion, and peak torso rotation. Head/knee excursion was the distance that the head/knee moves with respect to a fixed point (Z-point) on the testing buck, and torso rotation was measured at the rigid body representing the thorax and defined as the angle that goes past vertical direction.

Table A1 (see online Appendix) summarizes the range and mean of the input parameters of the parametric study in 1000 simulations. Uniform Latin hypercube sampling produced even distributions for the input parameters. The range of seat belt anchorage locations selected in this study were based on a large range of vehicle seat and belt configurations reported by a survey of second-row seating positions in late-model vehicles (Reed et al. 2008) that are within the allowable locations specified by FMVSS No. 210. The range of cushion lengths was obtained by measuring a sample of second- and third-row cushion lengths of 56 late-model vehicles (Huang and Reed 2006; Klinich et al. 2011). The position of the front column of the seat structure relative to the seat cushion was the same for all cushion lengths, and the position of the rear column of the seat structure was obtained by a linear interpolation from 2 validated seat models with long and short cushions. In real vehicles, the seat belt inboard and outboard anchors are often designed to achieve similar lap belt angles on both sides. Therefore, in this study, the 2 lap belt anchorages were moved forward and backward simultaneously.

In this study, statistical significance and effect size of every input parameter on each output variable were calculated. As an example, let the range of an input parameter A be split into 2 equal subranges, namely, lower range and upper range. Using the data from the design of experiment, a table consisting of the values of A and an output variable B can be populated. The mean of the values of variable B corresponding to the values of A that belong to the lower range of A was calculated as $B-$. Similarly, the mean of the values of variable B corresponding to the values of A that belong to the upper range of A was calculated as $B+$. The effect of the variable A on variable B was calculated as the difference between $B+$ and $B-$, and Student's t-test was performed between $B+$ and $B-$ to calculate the significance level. The effect size of A on B served as a good indicator of the influence of a variable on another variable; the sign of effect described the nature of influence (positive or negative) and the magnitude of effect described the level of influence. A ranking of all input parameters on each output variable can be achieved based on the effect size, providing an objective evaluation of the relative importance of each input parameter on each output variable over the range investigated.

Optimization of Restraint System for Improving 6-to 12-Year-Old Child Protection

For a rear-seat child in a frontal crash, the head and knee excursions are the major indicators of whether the head and knee will contact the front seat, causing head and lower extremity injuries. Therefore, in the current study, head and knee excursions were considered as the 2 objective functions to minimize in the restraint system optimizations. Because no head contact mechanism was simulated, injury measurements such as HIC and neck injury criteria (N_{ij}) calculated by MADYMO were not considered as objective functions. However, these injury measurements along with the chest acceleration and deflection were still monitored in the optimization, because stiffer restraint systems designed to reduce head and knee excursions may result in higher neck and chest loads. Previous studies (Klinich et al. 2010) have suggested that good child ATD kinematics in frontal crashes should include a peak torso rotation that goes forward past vertical by 10 to 20°. Insufficient forward torso rotation is associated with submarining, and forward torso rotation greater than 20° suggests a lack of torso control by the belt (rollout). Therefore, in this study, peak torso rotation was constrained to a range from 10 to 20°. Peak torso rotations beyond this range were treated as unfeasible designs and were not considered as optimal solutions. The ranges of input parameters in the design optimization were set to the same values used in the parametric study. Optimizations were conducted for 6-, 9-, and 12-year-old children separately to identify the difference among optimal designs for children with different sizes. A nondominated sorting genetic algorithm II (NSGA-II; Deb et al. 2002) was used to conduct each optimization. More than 50 generations were performed in an optimization with 50 designs in each generation, which resulted in more than 2500 simulations in each optimization.

Results

Restraint System Factor Effects on Injury Outcomes

Figure 2 summarizes the distributions of 3 output variables in the parametric study on factor effects, all of which were close to a normal distribution. The maximum head and knee excursions in this parametric study were 639 and 833 mm, respectively. Both of them were below the limits defined in FMVSS No. 213, in which head excursion should be less than 720 mm and knee excursion should be less than 915 mm. The highlighted (dark) designs are the feasible designs, in which peak torso rotations were within the optimal range of 10–20°, indicating good kinematics. Among these designs, over 76 percent were for children over 10 years old. Peak torso rotations in feasible designs were only on the right side of the distribution, indicating that children aged from 6 to 12 tend to sustain less torso rotation (submarining kinematics) during frontal crashes. Head excursions in feasible designs were aligned more toward the right (high), because relatively large head excursions are associated with large torso rotations, and the feasible designs were almost evenly distributed in the full range of knee excursion. The distributions of head excursion and peak torso rotation were unimodal, but the knee excursion distribution had multiple peaks. The 3 peaks correspond to the knee excursion distribution of 3 age groups, as shown in Figure 2d. For each age group, knee excursion distributed in a nearly normal distribution fashion and accounted for one peak of the whole knee excursion distribution. This indicated that body size had a dominant effect on knee excursion.

The effects of different design parameters on 3 output variables, including head excursion, knee excursion, and peak torso rotation, are shown in Figure 3. An effect size greater than 0 indicates a positive effect, and values less than 0 indicate a negative effect. In Figure 3, the design parameters were ranked based on the absolute values of the effect sizes.

Body size, represented by age in the analysis, was the most significant factor, with positive effects on all 3 output variables. The increase in excursions with body size indicated that the likelihood of head and knee impacting the vehicle increased for larger children. Small children were more likely to submarine or fail to achieve sufficient forward torso rotation for any particular belt configuration. However, the 3 belt anchorage locations had significant, but conflicting, effects on the 3 output variables. For example, by moving the D-ring rearward, lower and laterally closer to the ATD, the head excursion decreased significantly (good), but the peak torso rotation decreased as well (bad). By moving the 2 lap belt anchorages backward or moving the inboard anchor higher,

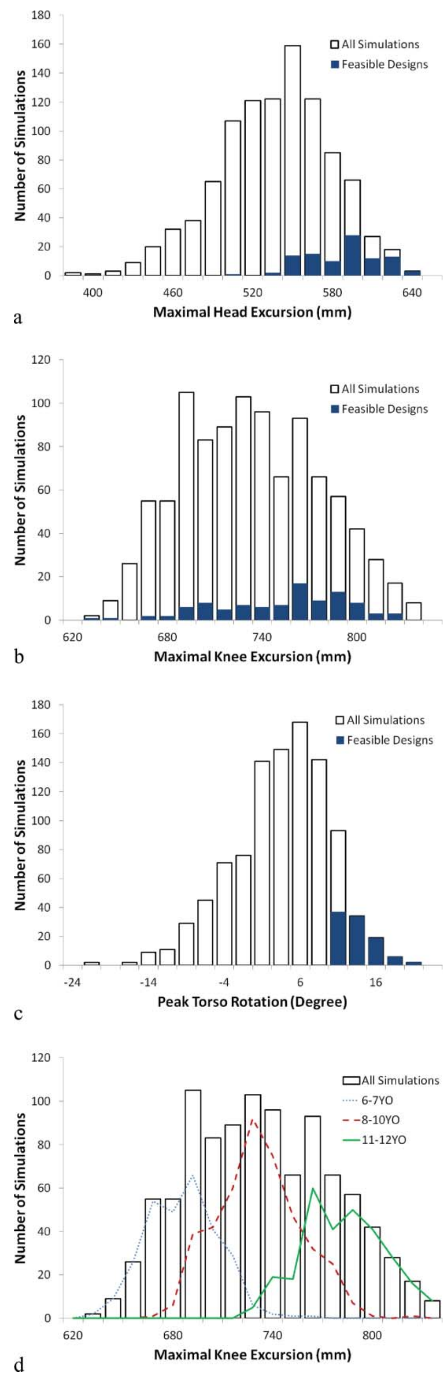

Fig. 2. Distribution of different output variables: (a) distribution of head excursion, (b) distribution of knee excursion, (c) distribution of peak torso rotation, and (d) distribution of knee excursion by age group. The absolute value of effect sizes of input factors decreases from the top to the bottom, and an asterisk indicates statistical significance ($P < .05$). Coordinates in reference to the H-point of the seat as the origin; $X+$ forward, $Y+$ inward, and $Z+$ upward (color figure available online).

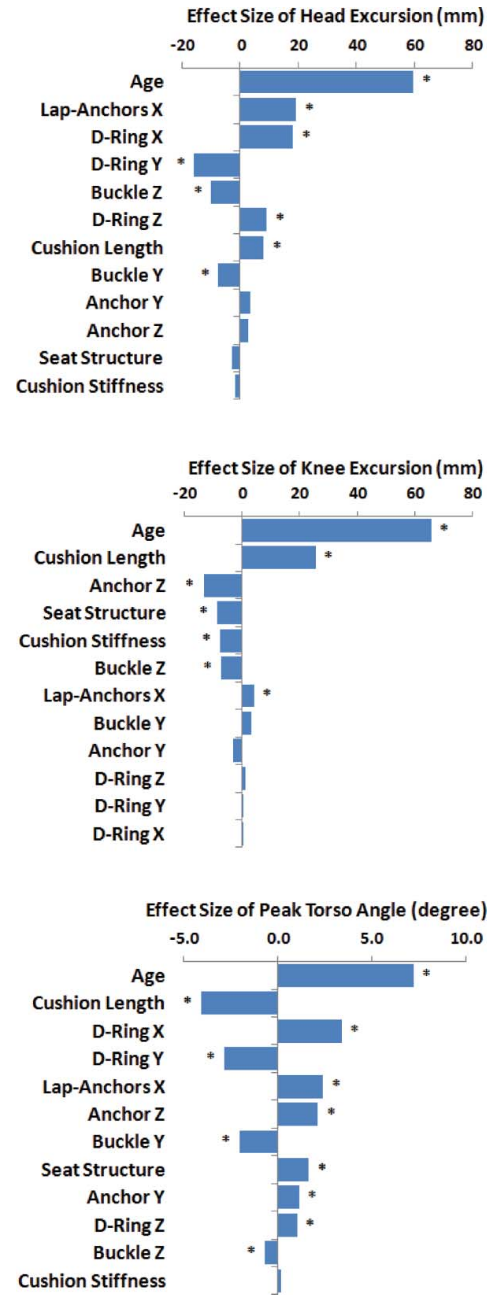

Fig. 3. Effect sizes of design parameters on head excursion, knee excursion, and torso rotation. The absolute value of effect sizes of input factors decreases from the top to the bottom, and an asterisk indicates statistical significance ($P < .05$). Coordinates in reference to the H-point of the seat as the origin; $X+$ forward, $Y+$ inward, and $Z+$ upward (color figure available online).

all 3 output variables decreased significantly, in which reducing excursions is good but reducing torso rotation is bad. By moving the outboard anchor higher, the knee excursion decreased and the peak torso rotation increased significantly, both of which are beneficial for child protection. By moving the inboard anchor point laterally farther from the ATD, the head excursion decreased (good) but the peak torso rotation also decreased (bad).

Cushion length had significant effects on all 3 output variables, especially for knee excursion and peak torso rotation. Reducing cushion length could decrease both head and knee excursion and increase peak torso rotation, all of which are beneficial for protecting child passengers. Seat structure had significant effects on knee excursion and peak torso rotation but an insignificant effect on head excursion. Moving the cushion-supporting structure higher reduced knee excursion and increased peak torso rotation. Increased cushion stiffness did not affect the head excursion and peak torso rotation but reduced knee excursion.

Restraint System Design Optimization

Because both head excursion and knee excursion were minimized in the optimizations, no single optimal solution could be achieved. As a result, 3 sets of Pareto-optimal designs were determined through optimizations for 6-, 9-, and 12-year-old children, respectively. Figure 4 shows optimization design histories of 2 objective functions for 12-year-old children, in which the knee excursion decreased significantly and reached a stable value around 40 generations (50 designs in each generation). The head excursion also reduced and converged at a stable value for 12-year-old children. However, in optimizations for 6- and 9-year-old children, the head excursion did not converge to the lowest value due to the constraints from torso rotation. The feasible designs in Figure 4 are those with peak torso rotation between 10 and 20°, indicating good kinematics, and the most unfeasible designs are those with peak torso rotation lower than 10°, indicating a trend toward submarining. In all simulations, only a few predicted peak torso rotation greater than 20°, suggesting that the likelihood of rollout was relatively low within the range of belt and seat configurations studied. It should be noted that, in reality, children sit in a wide range of ways in vehicles. The variation in seating postures may produce higher rollout risk than that predicted in the current study.

Figures 5 and 6 are the side and front views of 3 anchorage locations with respect to the seat H-point in all Pareto-optimal designs for 6-, 9-, and 12-year-old children. The optimal inboard and outboard anchor positions converged at the upper bound of the design spaces for children with different body sizes. However, the optimal inboard and outboard anchor positions for children with larger body size were located more rearward than those for children with smaller body sizes. The optimal inboard and outboard anchor locations for children with different body sizes were very close to each other laterally. The optimal anchor positions were at the upper-inner corner of the design space, and the optimal inboard anchor positions were near the middle of the upper bound of the design space, slightly toward the inner side. The optimal D-ring positions for 6-year-old children were located in the middle of the lower bound of the design space, and optimal D-ring positions for 12-year-old children were more rearward and higher than those for 6-year-old children. The optimal D-ring positions for 9-year-old children were between those for 6- and 12-year-old children. The optimal D-ring positions for children with different body sizes were all in the middle of the design space laterally.

Optimization results also showed that the shortest seat cushion length was optimal for all child sizes, as was the highest seat supporting structure. The ranges of optimal restraint system configurations for 6-, 9-, and 12-year-old children are shown in Table A2 (see online Appendix).

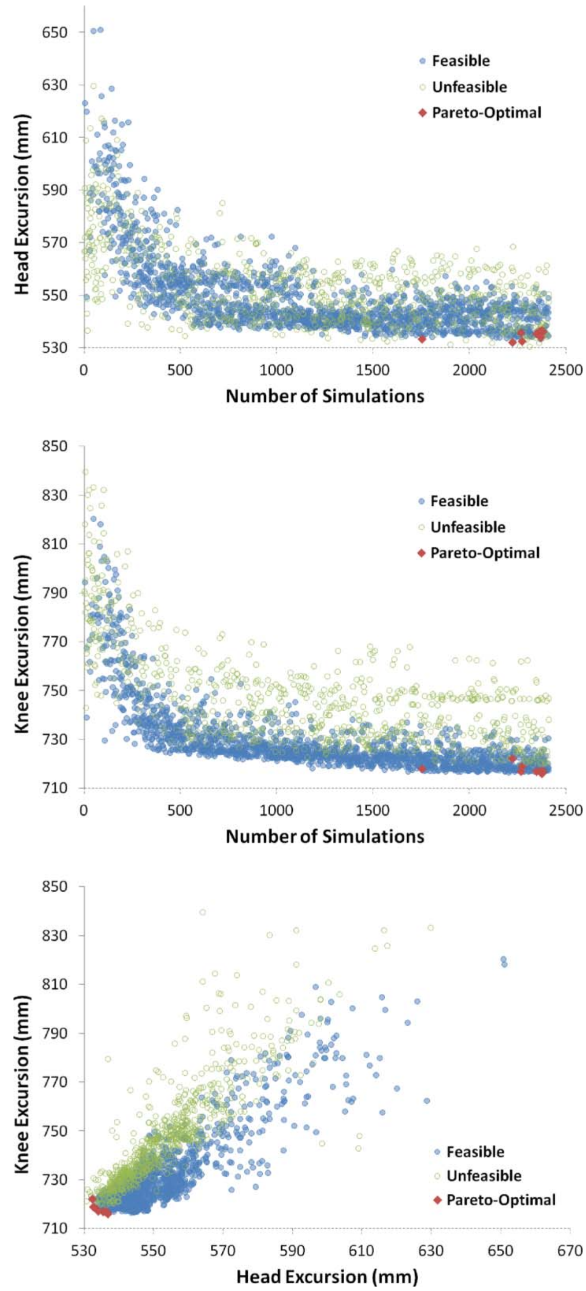

Fig. 4. Simulation histories of 2 objective functions in optimization for 12-year-old children. Feasible: peak torso rotation distributed in the range from 10 to 20°. Unfeasible: peak torso rotation beyond the ideal range (color figure available online).

It should be noted that the HIC, N_{ij}, and chest acceleration/deflection values were all below the injury criteria when using the optimal restraint systems, indicating that the design optimizations did not induce unintended consequences.

Discussion

Factor Effects on Occupant Kinematics

Body size, which was represented by age in this study, was the most dominant factor for all 3 injury measurements; that is, head excursion, knee excursion, and torso rotation. As the stature and weight increased, the head and knee excursions

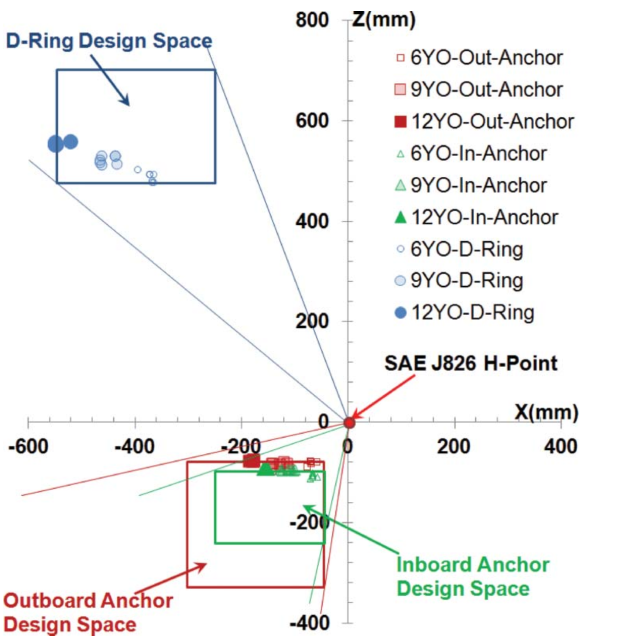

Fig. 5. Side view of Pareto-optimal locations of 3 seat belt anchorages for 6-, 9-, and 12-year-old children (color figure available online).

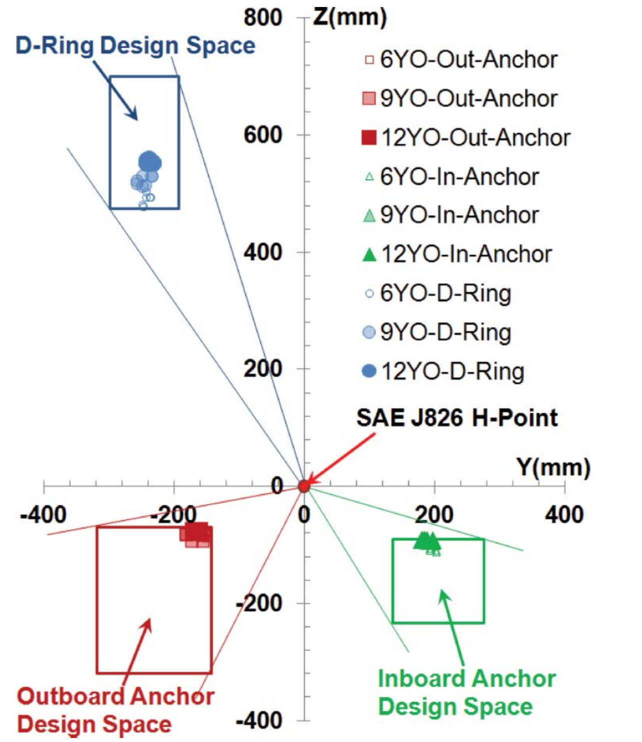

Fig. 6. Front view of Pareto-optimal locations of 3 seat belt anchorages for 6-, 9-, and 12-year-old children (color figure available online).

both increased significantly for 2 reasons. First, the head/knee excursion is the distance that the head/knee moves with respect to a fixed point (Z-point) on the testing buck. Therefore, a larger body size will lead to a more forward initial position before the impact, contributing to greater final head and knee excursions during a crash. Second, a longer torso will result in a longer moment arm for the head and thorax mass relative to the pelvis, consequently producing greater head excursion with the same torso rotation. However, children with large body sizes (over 10 years old) accounted for most (76%) of the simulations that resulted in feasible designs; that is, with good occupant kinematics. In contrast, only a relatively narrow range of restraint and seat conditions produced good kinematics for the smallest children. Under the same length of seat cushion, small-sized children are more likely to have slouched seating posture, causing poor lap belt fit. In addition, small-sized children have a lower shoulder height, which would also cause poor shoulder belt fit by placing the shoulder belt too close to the neck. These findings are consistent with other studies (Bilston and Sagar 2007), where rear seat geometry and belt geometry from 50 vehicles in recent model years were used to conclude that a substantial mismatch existed between the rear seating environment and children under 15 years old.

Seat belt anchorage locations also had significant effects on ATD responses. The inboard anchor and the D-ring (upper anchorage) locations contributed to the shoulder belt fit and hence significantly affected the head excursion. The inboard and outboard anchors contributed to the lap belt fit and thus significantly affected the knee excursion. The peak torso rotation, reflecting the whole ATD kinematics, was affected by both shoulder belt fit and lap belt fit, which were significantly affected by all 3 anchorage locations. Peak torso rotation was specified to be within 10 to 20° forward of vertical to avoid submarining (less forward rotation) or rollout (more forward rotation). However, in the current study, the rollout condition rarely occurred, indicating that the more challenging goal in achieving good ATD kinematics for 6- to 12-year-old children is to avoid low levels of torso rotation associated with a higher likelihood of submarining. The results showed that the effects from 3 anchorage locations on peak torso rotation were consistent with those on the head excursion but opposite those on the knee excursion, because a large head excursion and small knee excursion correspond to a large forward torso rotation and vice versa. It should be noted that the criterion for good kinematics with peak torso rotation from 10 to 20° was based on previous sled test data by Klinich et al. (2011). Further studies are needed to investigate whether changing this criterion with different torso rotation ranges will significantly affect the final optimal designs for children with different body sizes.

Seat parameters also had significant effects on ATD responses. Cushion length, which affected the initial seating posture of the occupant, had significant effects on all 3 output variables. Reducing the length of the seat cushion allows occupants, especially small children, to sit more rearward and upright, improving both shoulder belt fit and lap belt fit, which would result in decreased head and knee excursions and increased peak torso rotation. This is consistent with the findings of Klinich et al. (2011), who reported that shortening the seat cushion length could improve the kinematics of 6- and 10-year-old child dummies. However, reducing cushion length to a certain level has the potential to reduce protection for children in rear-facing child restraints or adults. Future studies on cushion length should try to balance protection among older child occupants, infants in infant seats, and adult occupants. In this study, the seat structure represents the location of the cushion-supporting structures. Moving the seat cushion-supporting structure higher is equivalent to reducing the cushion thickness and increasing the stiffness of cushion-supporting structures, which will lead to an earlier and stiffer leg-to-seat contact and, in turn, reduce the knee excursion and the risk of submarining. A strong cushion-supporting structure and thin cushion can better protect older child occupants but with a cost of riding comfort, which needs to be considered in the future. Seat cushion stiffness had a similar effect on knee excursion as seat structure but was not as significant.

Restraint System Design Optimization

As shown in Figure 3 and Table A2, the optimal restraint system designs were generally in good agreement with the factor effects from the parametric study. In the design space selected in the current study, a lower and more rearward D-ring, higher and more forward inboard and outboard anchors, and a shorter, thinner, and stiffer seat cushion produced better kinematics in frontal impacts. However, there were slight differences among 6-, 9-, and 12-year-old children in terms of optimal seat belt anchorage locations. In particular, children with larger body size were less likely to exhibit submarining-type kinematics, which allowed the optimization to move the inboard and outboard anchors more rearward to reduce the knee excursion while keeping the torso rotation within the acceptable range. The optimal D-ring locations for 6-year-old children were more forward than those for 12-year-old children, even though more rearward D-ring location could reduce head excursion. This was because 6-year-old children require more-forward lower anchorages (steeper lap belt angles) to obtain proper pelvis restraint. Consequently, the D-ring location must be more forward to maintain the peak torso angle in the acceptable range. The optimization approach described here is well suited for dealing with these conflicting objectives.

The parameter ranges of the Pareto-optimal restraint systems were fairly small in this study due to the emphasis on providing better protection for only 6- to 12-year-old children. However, more research is needed to determine whether the optimal designs for this age group might have adverse effects on adult occupants or children in harness restraints. It may also be difficult to directly apply findings to a specific passenger vehicle because of the limited design space and layout of the rear compartment. An adaptive restraint system that can adjust the length of the cushion and position of the belt anchorage to meet the needs of different occupant sizes could be a way to provide optimal restraint to a wide range of occupant sizes.

The results of this study showed that typical second-row seat cushion lengths and belt anchorage locations do not provide optimal protection for children in this age range. With the current rear-seat environments, transitioning children out of boosters after age 8 years may have an adverse effect on frontal crash protection. Reed et al. (2008) found that the smallest children experienced approximately the same average lap belt fit in the worst-performing booster as the largest children did without a booster. Klinich et al. (2011) indicated that the kinematics of both 6- and 10-year-old dummies in tests with the shorter cushion length were worse than tests with booster seats. Bilston and Sagar (2007) also pointed out that current seat cushion length and shoulder belt geometry were unsuitable for children seated on the real seat. Therefore, the recent recommendations for extending booster use until the child can fit well in the vehicle belts alone can be another solution to provide better protection for older child occupants.

Limitations

This study has several important limitations. First, the parametric child ATD model used in the current study was developed and validated against HIII 6- and 10-year-old ATDs. However, the HIII child ATDs are essentially scaled from the HIII midsize adult male ATD, and their biofidelity, especially on the spine, pelvis, and shoulder regions, has been questioned and needs further improvement. A more biofidelic child model might result in changes in the optimal belt configurations. Several previous studies have attempted to improve the biofidelity of the child ATD at different body regions. Klinich et al. (2010) developed a more realistic pelvis for the 6-year-old HIII ATD based on the skeletal geometry data from Reed, Sochor, et al. (2009). Hu et al. (2012) further incorporated these design changes into a 6-year-old HIII MADYMO ATD model. Both sled tests and computational simulations showed that the new pelvis along with the new abdomen was more sensitive to lap belt geometry and thus capable of predicting submarining in frontal crashes. Sherwood et al. (2003) explored the effect of adding a revolute joint at the thoracic spine of a 6-year-old HIII MADYMO model and found that decreased thoracic spinal stiffness can result in more biofidelic impact responses. More recently, biomechanical impact test data on pediatric neck (Dibb 2011) and whole-body kinematics (Arbogast, Balasubramanian, et al. 2009) have also been reported. Future efforts using these data to improve the child ATD designs will likely lead to a more biofidelic child ATD as well as more realistic optimal restraint system designs for older children.

Second, this study is limited by the fact that only one median set of body dimensions and segment masses was used for each age, and only a single posture and belt fit was simulated for each combination of seat length and body size. In reality, dimension and mass distributions may vary significantly for children even with the same height and weight, and posture and belt fit also vary considerably (Reed et al. 2008). Moreover, only a single frontal impact condition was used in this study. Further research is needed to determine whether the results reported in this study are robust to variance in these areas.

Third, in this study, the ranges of most design parameters were based on the vehicle measurements reported by previous studies. However, many optimal designs were located at the design limits, suggesting that more research is needed to explore design alternatives beyond the current design space. We have not attempted to quantify the safety cost of various levels of head and knee excursions. The amount of space in the rear compartment varies with vehicle design and front seat position, but in general we expect small head excursions to avoid head contact in most vehicles and large head excursions to result in head contact in most vehicles. Consequently, the distribution of design space is an important consideration in future restraint system design optimizations. In addition, more injury measurements may be considered in future restraint system optimizations, and future sled tests are also necessary to validate the optimized restraint systems presented in this study.

Conclusions

In this study, an automated program was developed to integrate a parametric child ATD model, ATD positioning procedure, belt-fitting algorithm, and varying vehicle seat and seat belt systems into crash simulations. A parametric study and design optimizations were conducted using the newly developed computer program to investigate the effects of restraint system design parameters and to find restraint system designs that provided the best occupant kinematics for children ages 6 to 12 in frontal impacts. Body size had a dominant effect on kinematic outcomes. Based on these simulations, children with smaller body sizes require more-forward D-ring, inboard anchor, and outboard anchor locations to obtain good kinematics. The challenge of reducing head and knee excursions while maintaining good torso restraint indicates the value of an optimization approach that considers child body size.

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