CChIPS | Center for Child Injury Prevention Studies

EVALUATION OF POSTURE AND BELT FIT FOR BOOSTER-SEATED CHILDREN

Gretchen H. Baker, PhD

Injury Biomechanics Research Center, Ohio State University | Gretchen.Baker@osumc.edu

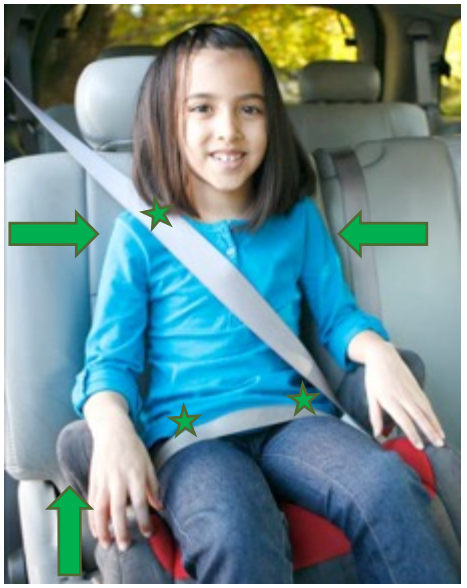
Child Occupant Protection: Latest Knowledge and Future Opportunities | 21 September 2022

Children's Hospital of Philadelphia RESEARCH INSTITUTE

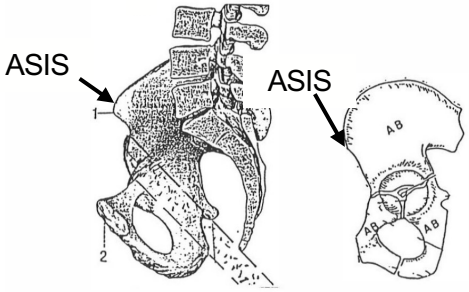
THE OHIO STATE UNIVERSITY WEXNER MEDICAL CENTER

BACKGROUND: BOOSTER SEATS

- Belt-positioning Boosters (BPBs) recommended for children too small to obtain proper fit in the adult seatbelt (4–12 years)
  - Shoulder belt → center of the clavicle
  - Lap belt → below the anterior superior iliac spine (ASIS) on pelvis
  - Centralize child position in vehicle
  - Raise seated height
  - Reduce slouching



[Safe Kids Worldwide, 2014]

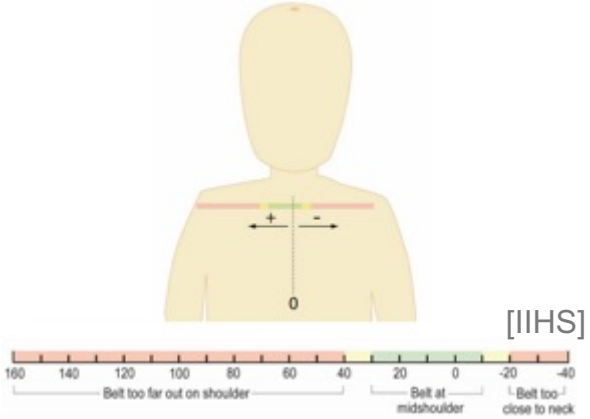


[Tarriere 1995]

- Tarriere C. CHILDREN ARE NOT MINIATURE ADULTS. In: *Proc. of Int. Conf. on the Biomechanics of Impacts (IRCOBI)*. ; 1995.

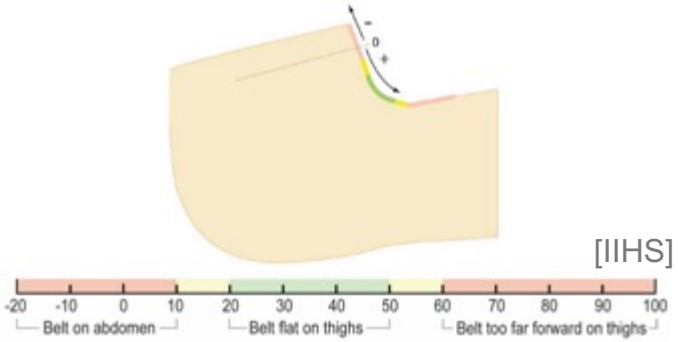
BACKGROUND: BELT FIT

Shoulder Belt Score (SBS)
[Klinich et al. 2008; Reed et al. 2009, 2013; IIHS]



[IIHS]

Lap Belt Score (LBS)
[Klinich et al. 2008; Reed et al. 2009, 2013; IIHS]



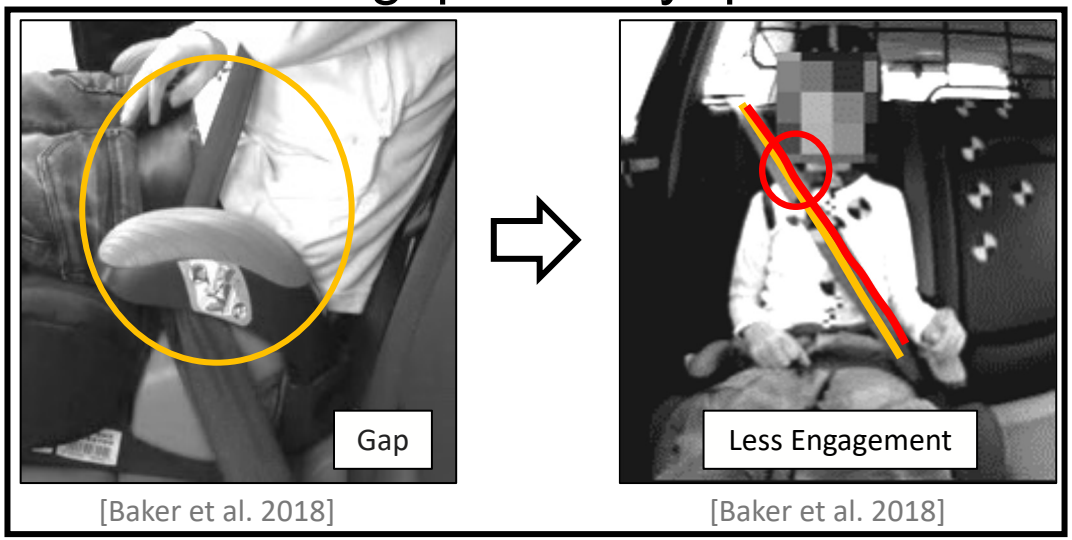
[IIHS]

- Boosters improve SBS and LBS compared to no-booster conditions
  [Klinich et al. 2008, 2020; Reed et al. 2009, 2013; Jones et al. 2020]
- Boosters with similar initial SBS and LBS do not necessarily provide similar dynamic outcomes [Klinich 2008, 2020]

- Klinich KD, et al. Assessing Child Belt Fit, Volume II: Effect of Restraint Configuration, Booster Seat Designs, Seating Procedure, and Belt Fit on the Dynamic Response of the Hybrid III 10YO ATD in Sled Tests. Technical Report, 2008, II, UMTRI-2008-49-2.
- Reed MP, et al. Evaluation of the static belt fit provided by belt-positioning booster seats. Accident Analysis and Prevention, 2009, 41:598–607.
- Insurance Institute for Highway Safety. Insurance Institute for Highway Safety Booster Seat Belt Fit Evaluation Protocol (Version II), 2011.
- Klinich KD, Ebert S, and Reed MP. Child posture and belt fit in second row vehicle seats. Technical Report, 2016, UMTRI-2015-35.
- Klinich KD, Jones MH, et al. Investigation of Potential Design and Performance Criteria for Booster Seats Through Volunteer and Dynamic Testing. Technical Report, 2020, DOT HS 812 919.
- Jones MH, Ebert S, Manary MA, Reed MP, Klinich KD. Child Posture and Belt Fit in a Range of Booster Configurations. International Journal of Environmental Research and Public Health, 2020, 17.

BACKGROUND: DYNAMIC STUDIES

- BPB-seated children evaluated during evasive vehicle maneuvers [Bohman et al. 2011; Stockman et al. 2013; Baker et al. 2017, 2018]
- Gap between shoulder belt and lower torso → less engagement between belt and torso during steering [Baker et al. 2018]
  - Belt slip-off → potentially unstable restraint scenario
- Belt fit and belt gap not fully quantified



[Baker et al. 2018] [Baker et al. 2018] [Baker et al. 2018]

- Baker, G. et al. Kinematics and shoulder belt engagement of children on belt-positioning boosters during evasive steering maneuvers. Traffic Inj. Prev. 19, S131–S138 (2018).
- Bohman, K. et al. Kinematics and shoulder belt position of child rear seat passengers during vehicle maneuvers. Ann. Adv. Automot. Med. 55, 15–26 (2011).
- Stockman, I., Bohman, K., Jakobsson, L. & Brolin, K. Kinematics of Child Volunteers and Child ATDs During Emergency Braking Events in Real Car Environment. Traffic Inj. Prev. 14, 92–102 (2013).

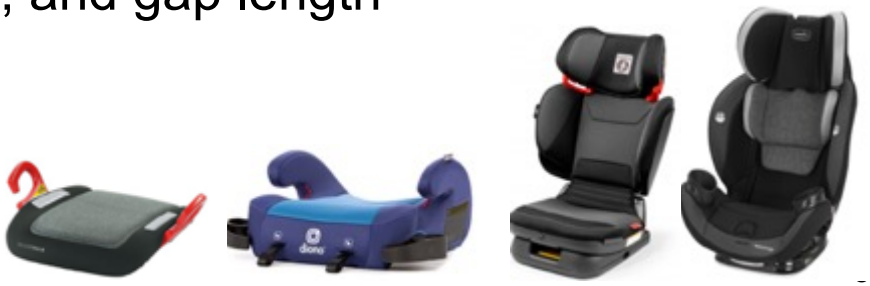
OBJECTIVE AND SPECIFIC AIMS

Objective:

To enhance understanding of posture and belt fit for children on boosters

<u>For a group of 50 child volunteers:</u>

1. **Quantify belt fit** utilizing conventional metrics
   - shoulder belt score and lap belt score
2. **Quantify belt gap** utilizing novel metrics
   - %belt-torso contact, gap size, and gap length
3. **Quantify child posture**
   - 3D motion capture system



METHODS: VEHICLE SEAT FIXTURE

Vehicle seat fixture in laboratory setting

- Recent model year sedan, left outboard seating position
- Seatbelt outlet integrated into rear shelf
- Simulated rigid buckle stalk

Lower seatbelt anchor positions

[Bing et al. 2015, 2018; FMVSS 210]

- ***Baseline***: 39 cm width, 52° to SRP
- ***Forward***: 39 cm width, 75° to SRP
- ***Wide***: 56 cm width, 52° to SRP

- Department of Transportation. NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION LABORATORY TEST PROCEDURE FOR FMVSS 210 Seat Belt Assembly Anchorages Office of Vehicle Safety Compliance. (1994).
- Bing, J. A., Agnew, A. M. & Bolte IV, J. H. Compatibility of booster seats and vehicles in the U.S. market. Traffic Inj. Prev. 19, 385–390 (2018).
- Bing, J. A., Bolte IV, J. H. & Agnew, A. M. Investigation of Child Restraint System (CRS) Compatibility in the Vehicle Seat Environment. Traffic Inj. Prev. 16, (2015).

METHODS: BOOSTERS

3in1 Rear-Facing (3in1)

Evenflo Everystage DLX

Safety 1st Grow and Go EX

Combination (Comb)

Britax Frontier ClickTight

Chicco MyFit

Highback (HB)

Baby Trend Protect Yumi

Peg Perego Viaggio Flex 120

Lowback (LB)

Cosco Topside

Diono Solana 2

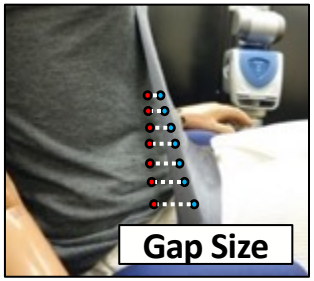
Low

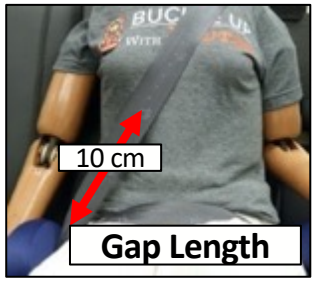
Mifold

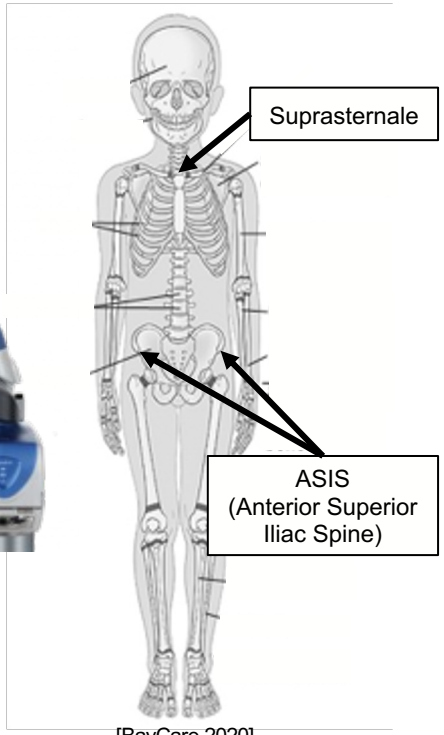
Graco Turbobooster SB Trainer

METHODS: DATA COLLECTION

- **FARO Edge Arm**
  - Quantify positions of seat, boosters, children, and belts
- **Posture**
  - Position of ASIS, Suprasternale
- **Belt Fit Metrics**
  - Shoulder Belt Score
  - Lap Belt Score
- **Belt Gap Metrics**
  - Gap Size
  - Gap Length
  - Gap Location
  - Torso Contact





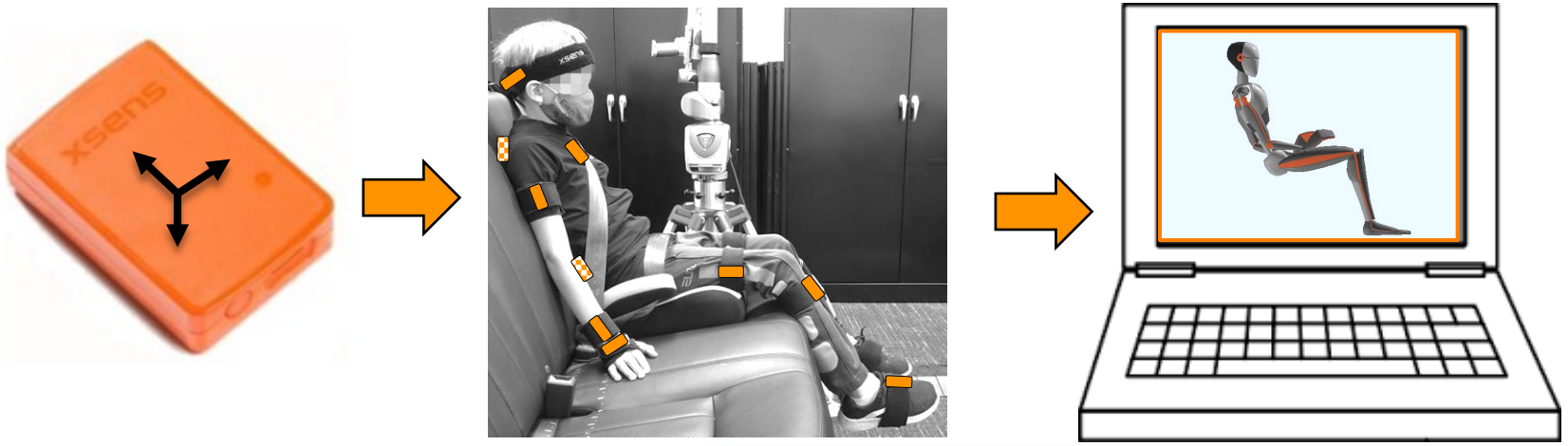


[BayCare 2020]

METHODS: DATA COLLECTION

IMU-Based Motion Capture System (XSENS)

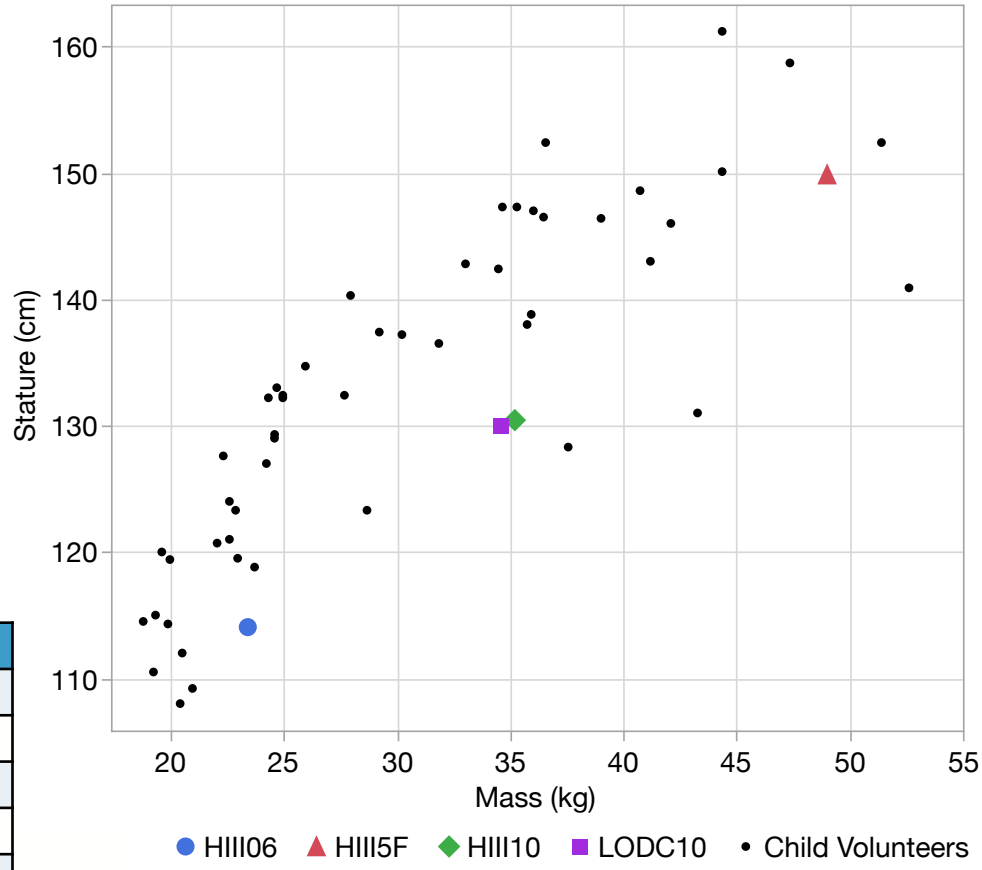
- 17 Inertial Measurement Units (IMUs)
  - 3-axis accelerometer
  - 3-axis angular rate sensor
  - 3-axis magnetometer
- Placed on head, torso, pelvis, extremities
- Anthropometry + XSENS Biomechanical Model + calibration
- Quantify all joint angles, body segment orientations at 60 Hz



METHODS: VOLUNTEERS

- Cohort of child volunteers (n=50)
  - Evaluated on 6 randomized conditions:
    - Booster
    - Seatbelt anchor location
  - 300 trials total

Metric	Mean	Std Dev	Min	Max
Age (yr)	8.5	2.5	4	14
Mass (kg)	30.3	9.2	18.8	52.6
Stature (cm)	132.9	13.5	108.0	161.2
BMI	16.8	2.8	13.6	26.5
CDC Percentile	48.0	29.9	3.0	99.0



RESULTS: BOOSTER SEATS


Boost


Seat Length


Seat Angle


Back Angle


Angle b/w Back and Seat

3in1, Comb, HB

- Medium seat length
- Greatest boost
- Less horizontal boosters seat angle
- Smaller angle between booster seat and back

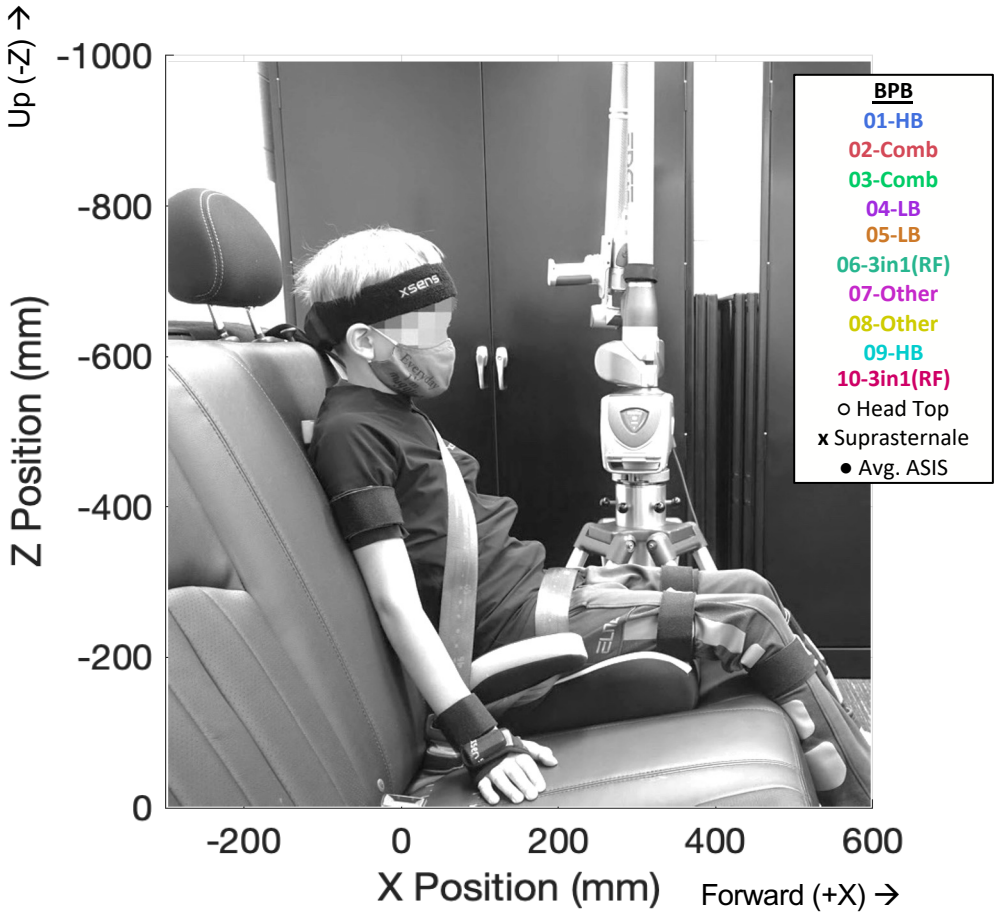
LB

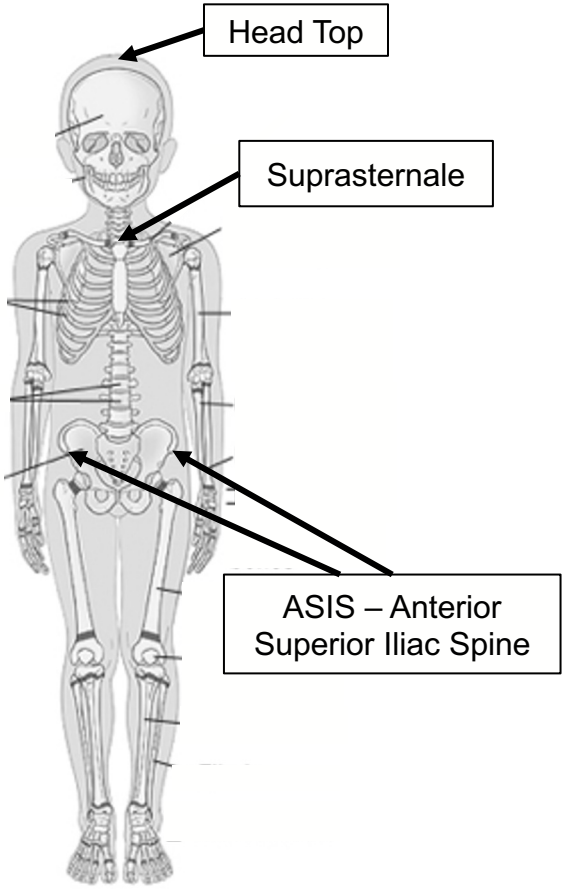
- Longest seat length
- Medium boost
- More horizontal booster seat angle
- Larger angle between booster seat and vehicle seatback

Other/Low

- Shortest seat length
- Lowest boost
- Most horizontal booster seat angle
- Largest angle between booster seat and vehicle seatback

RESULTS: POSTURE

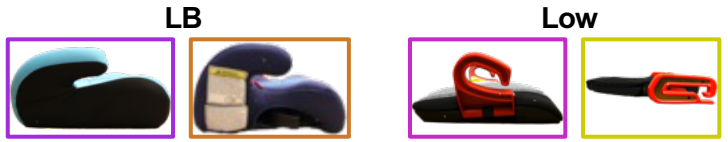




[BayCare 2020]

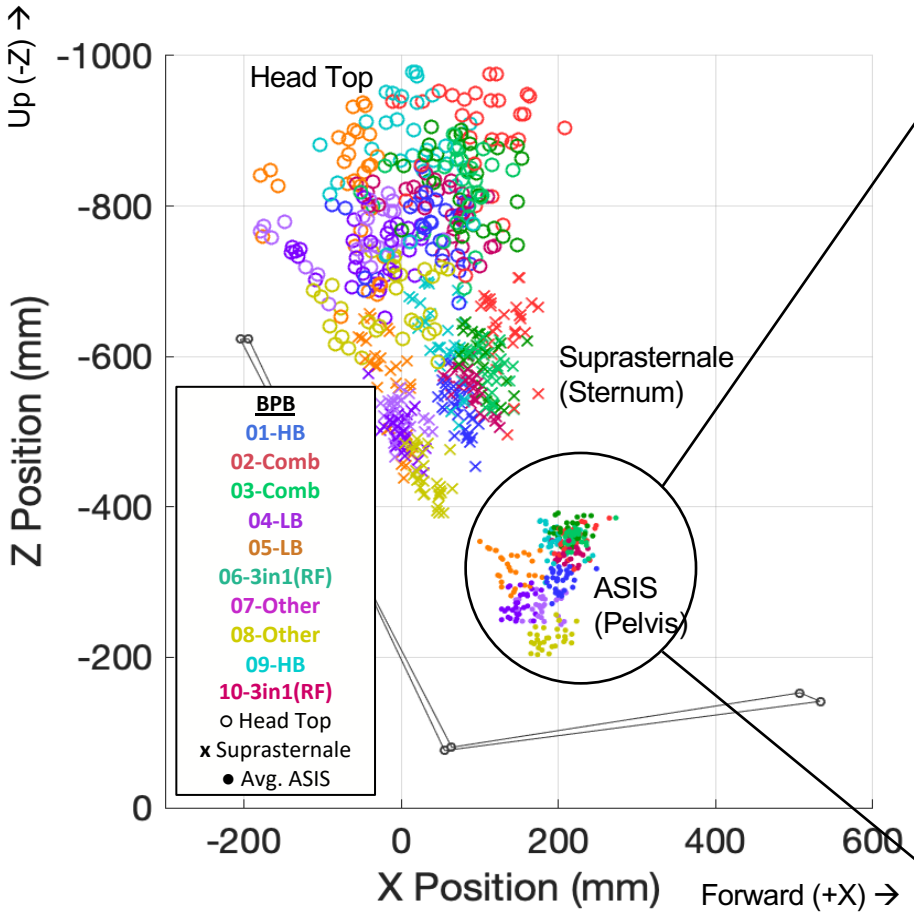
- Baker GH, Mansfield JA, Hunter RL, Bolte IV JH. Application of an Inertial Measurement Unit (IMU)-Based Motion Capture System for the Quantification of Child Posture on Belt-Positioning Booster Seats. In: *Protection of Children in Cars Conference*. Virtual; 2021.

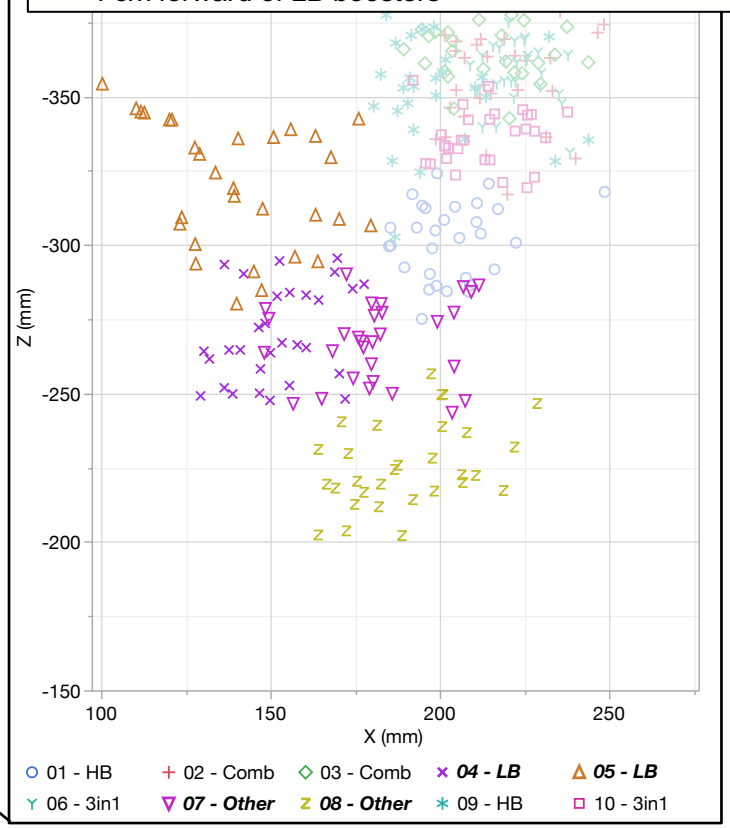
RESULTS: POSTURE



LB Boosters
- 5 cm lower than boosters with backs (HB/Comb/3in1)

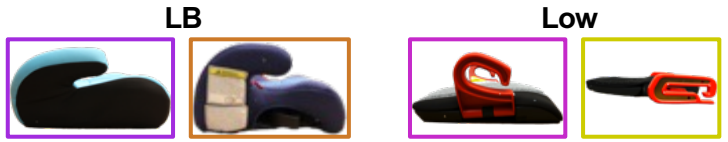
Low Boosters
- 10 cm lower than boosters with backs (HB/Comb/3in1)
- 4 cm forward of LB boosters





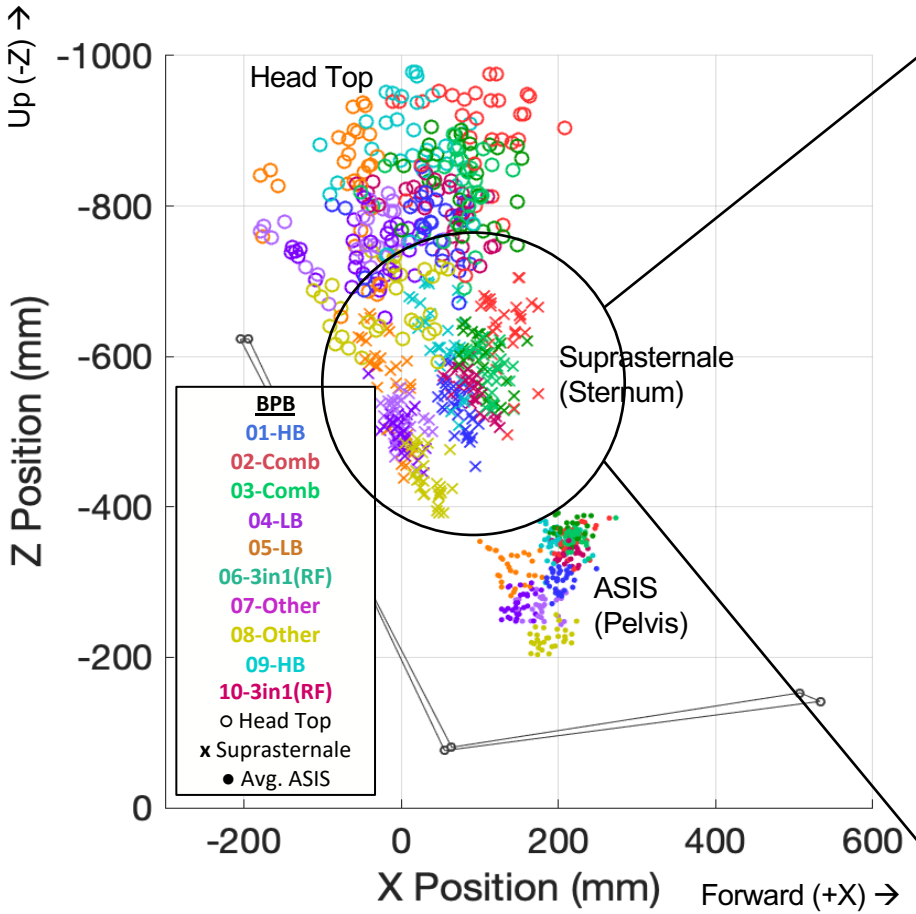
- Baker GH, Mansfield JA, Hunter RL, Bolte IV JH. Application of an Inertial Measurement Unit (IMU)-Based Motion Capture System for the Quantification of Child Posture on Belt-Positioning Booster Seats. In: *Protection of Children in Cars Conference*. Virtual; 2021.

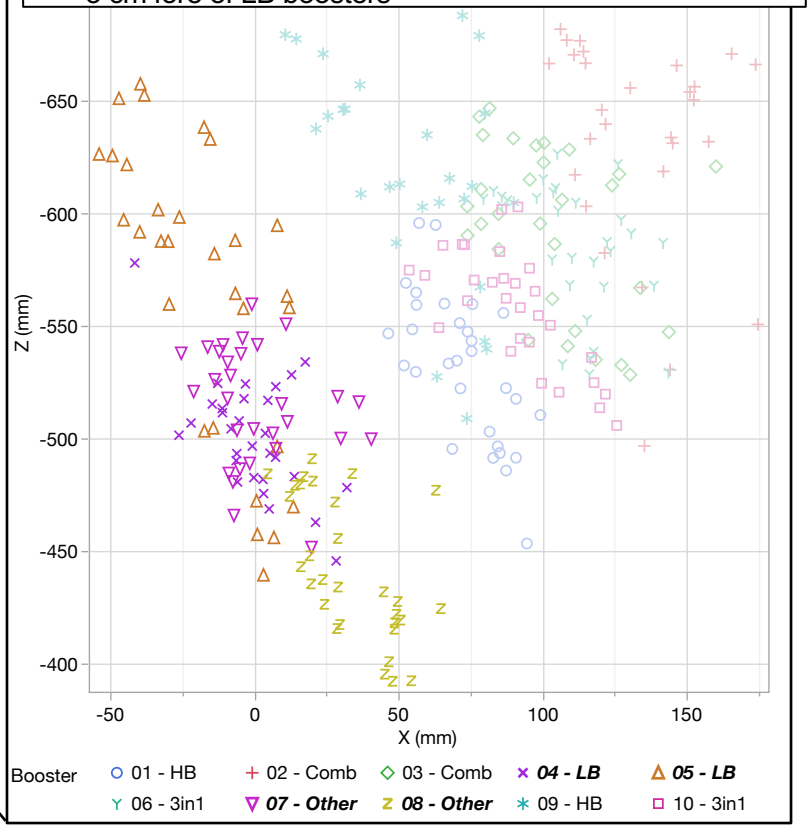
RESULTS: POSTURE



LB Boosters
- 5 cm lower than boosters with backs (HB/Comb/3in1)

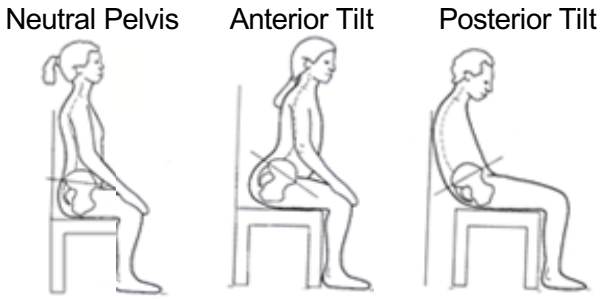
Low Boosters
- 11 cm lower than boosters with backs (HB/Comb/3in1)
- 3 cm fore of LB boosters





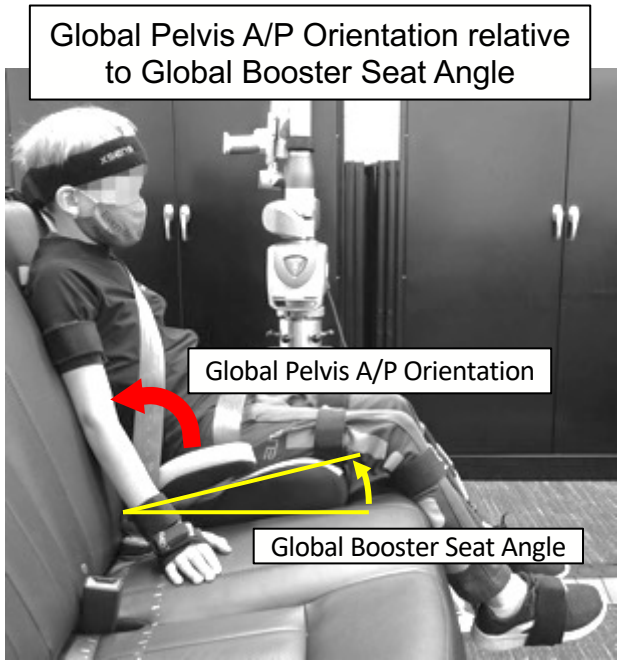
- Baker GH, Mansfield JA, Hunter RL, Bolte IV JH. Application of an Inertial Measurement Unit (IMU)-Based Motion Capture System for the Quantification of Child Posture on Belt-Positioning Booster Seats. In: *Protection of Children in Cars Conference*. Virtual; 2021.

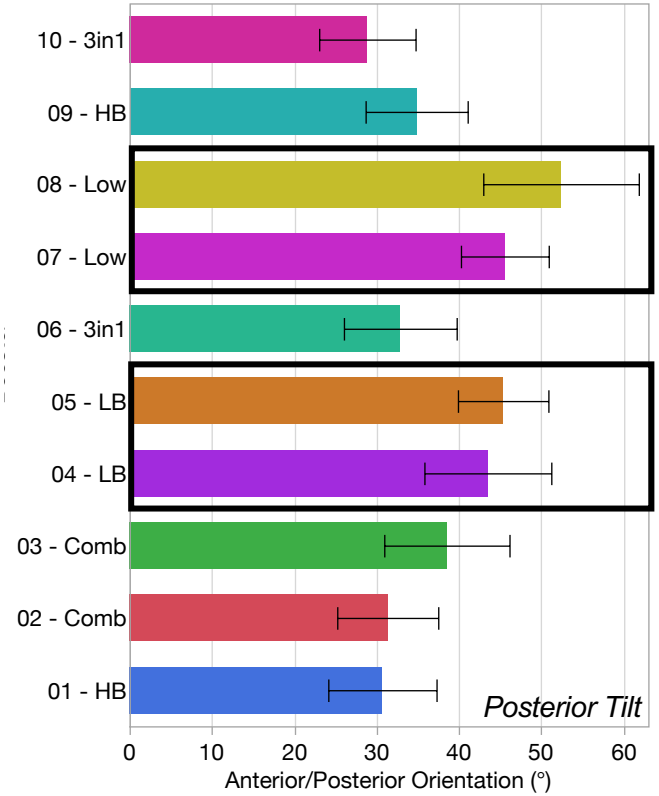
RESULTS: POSTURE



[Zollars 1996]

Average Pelvis Anterior/Posterior (A/P) Orientation





LB, Low Boosters

- More posteriorly rotated pelvis by 13° on avg.
  - May indicate slouched posture

- Zollars, J. A. (1996). Special seating: An illustrated guide. Minneapolis, MN: Ottobock Orthopedic Industry.
- Baker GH, Mansfield JA, Hunter RL, Bolte IV JH. Application of an Inertial Measurement Unit (IMU)-Based Motion Capture System for the Quantification of Child Posture on Belt-Positioning Booster Seats. In: *Protection of Children in Cars Conference*. Virtual; 2021.

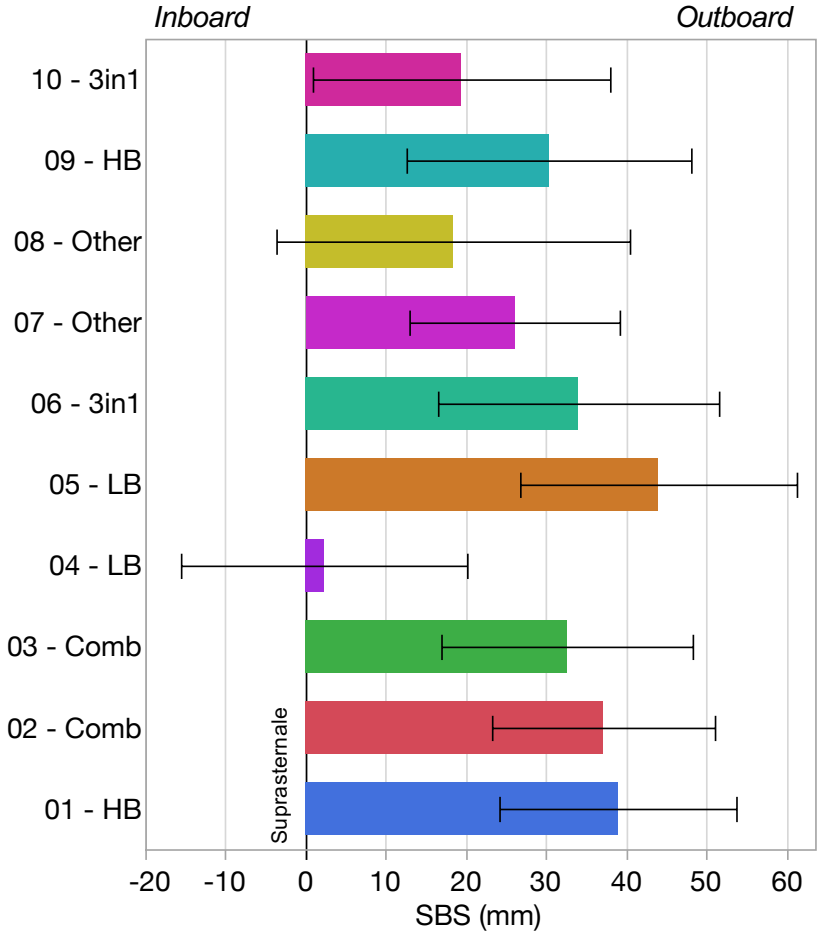
RESULTS: SHOULDER BELT FIT

ANOVA
$p<0.0001$
$R^2_{Adj} = 0.3061$

- SBS within similar range for most boosters
- LB → most extreme SBS
  - **04-LB**: most inboard
  - **05-LB**: most outboard

Over armrest belt routing

Flexible belt guide



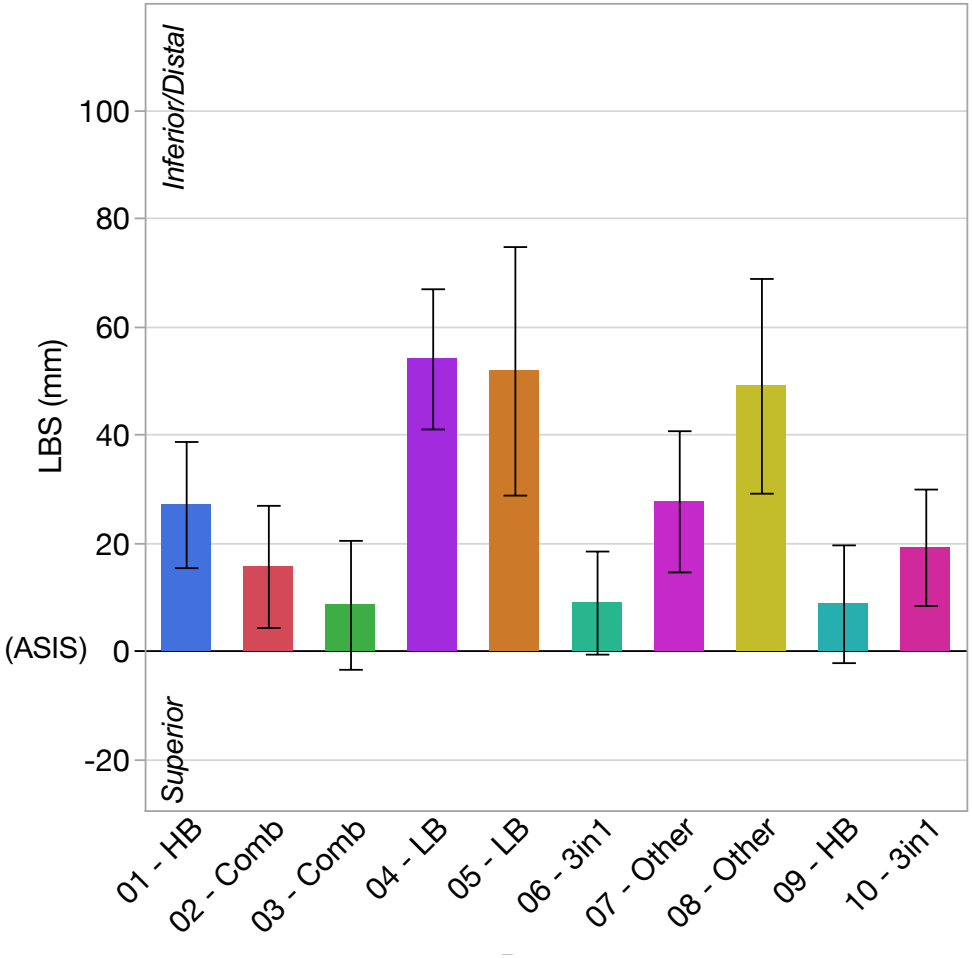
- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

RESULTS: LAP BELT FIT

ANOVA
$p<0.0001$
$R^2_{Adj} = 0.5987$

- LBS varied significantly between boosters
- Belt routing features pull lap belt forward, contributing to inferior/distal LBS

Under armrest LB routing | Under armrest LB routing | Through clip LB routing

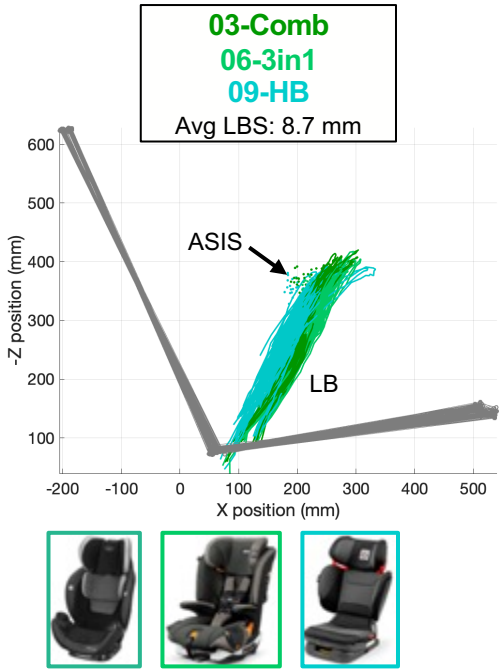


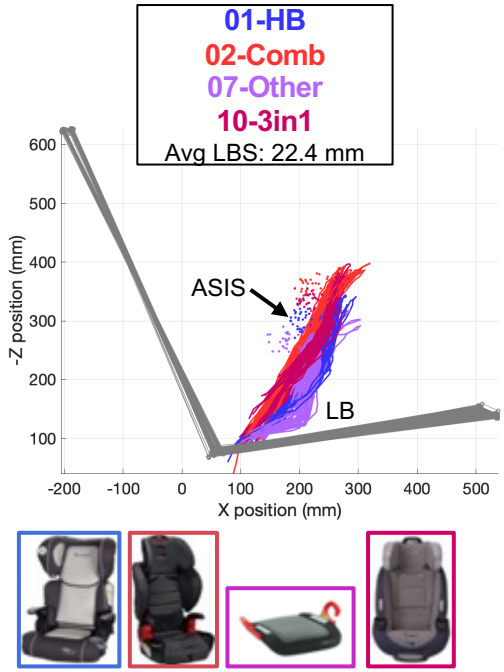
- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

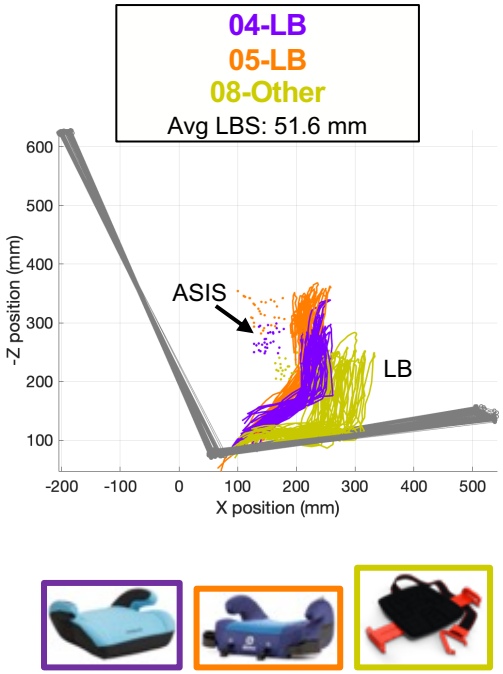
RESULTS: LAP BELT FIT

ANOVA
$p<0.0001$
$R^2_{Adj} = 0.5987$

- Belt routing features pull lap belt forward → contributes to more inferior/distal LBS

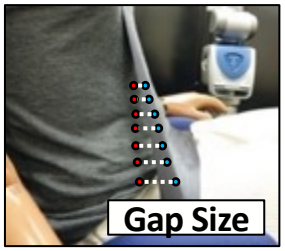


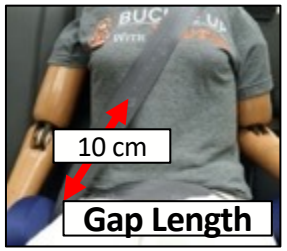




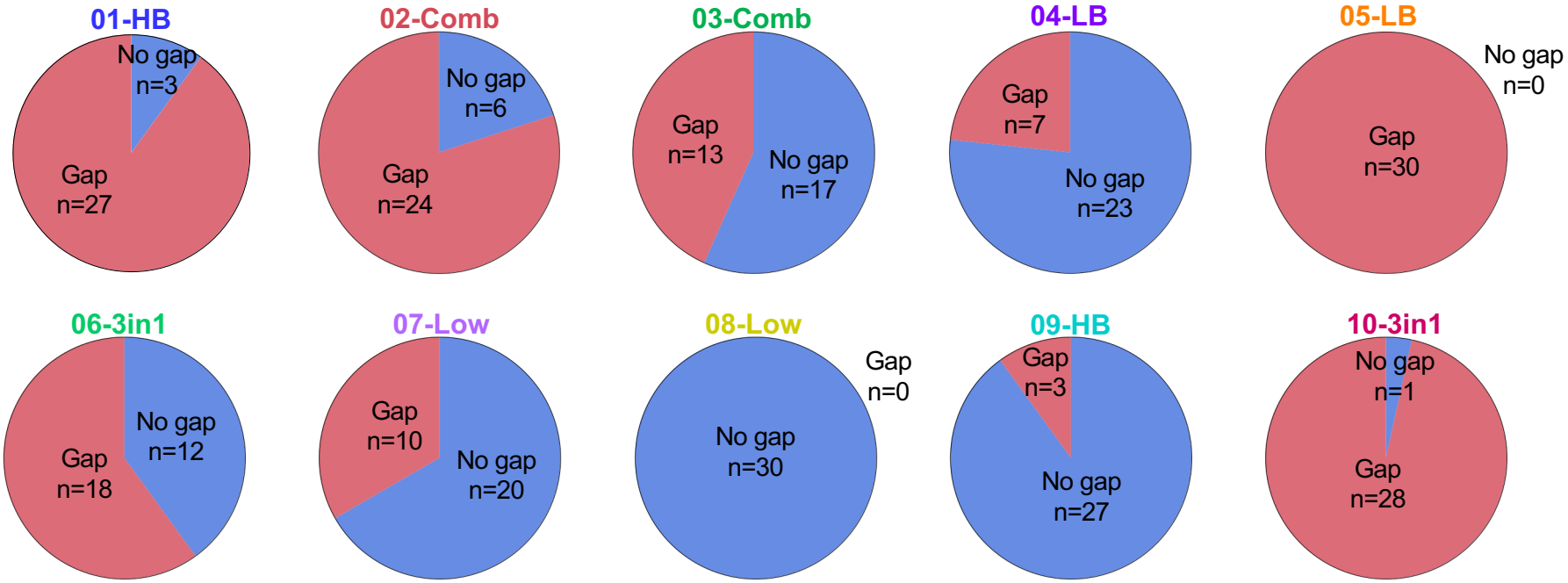
- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

RESULTS: BELT GAP



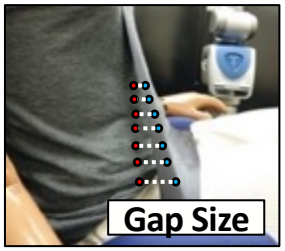


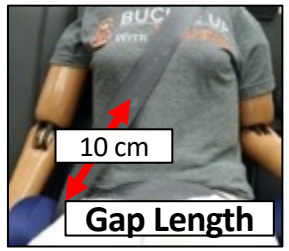
Number of Children with Identified Belt Gap Region



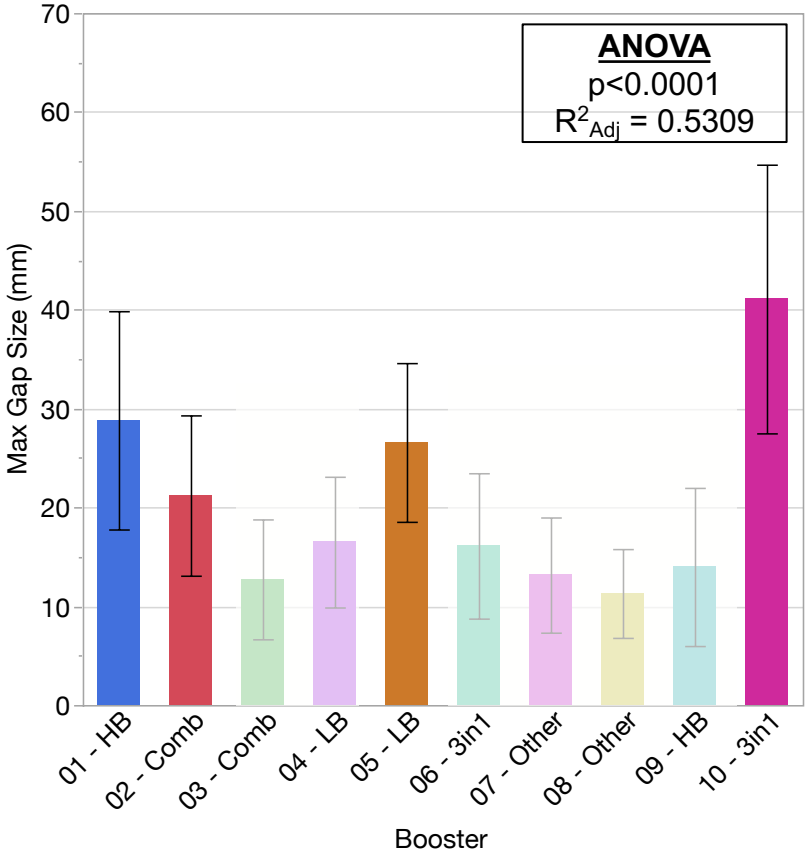
- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

RESULTS: BELT GAP

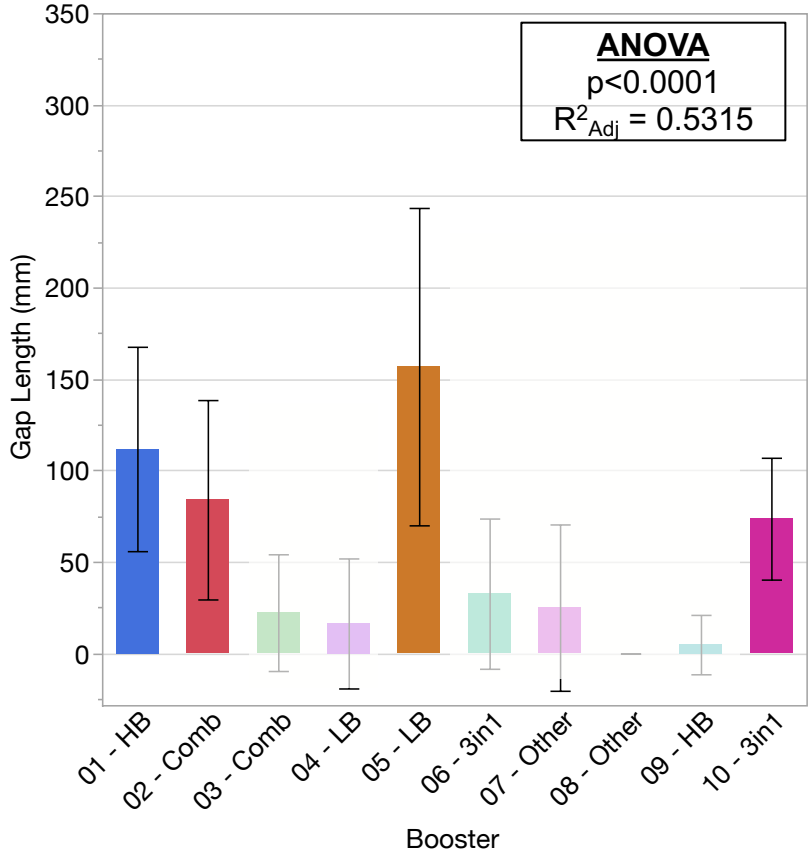




Maximum Gap Size



Gap Length



- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

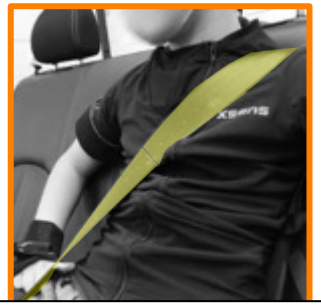
Average of Boosters 1, 2, 5, 10
Gap Length = 106.7 mm
Max Gap = 29.4 mm

RESULTS: BELT GAP

- **Greatest & longest gap** → Inboard routing pulls belt forward

01-HB
Gap Length = 111.8 mm
Max Gap = 28.8 mm

02-Comb
Gap Length = 87.0 mm
Max Gap = 21.2 mm



05-LB
Gap Length = 156.9 mm
Max Gap = 26.6 mm

10-3in1
Gap Length = 71.3 mm
Max Gap = 41.1 mm

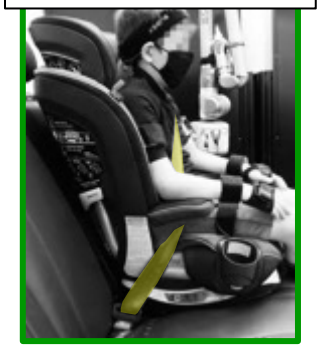
- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

RESULTS: BELT GAP

Average of BPBs 3, 4, 6, 7, 8, 9
Gap Length = 16.9 mm
Max Gap = 14.0 mm

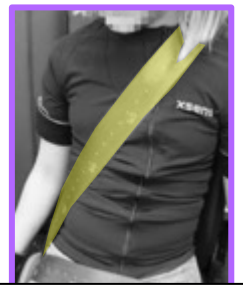
- **Smallest & shortest gap** → No direct inboard belt routing or belt guide does not pull belt far forward

03-Comb
Gap Length = 22.4 mm
Max Gap = 12.7 mm

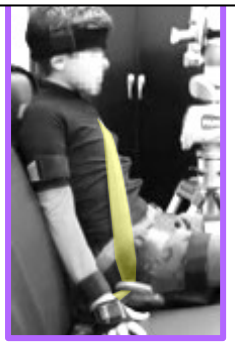


04-LB
Gap Length = 16.5 mm
Max Gap = 16.5 mm

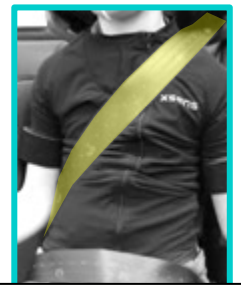
06-3in1
Gap Length = 32.8 mm
Max Gap = 16.1 mm



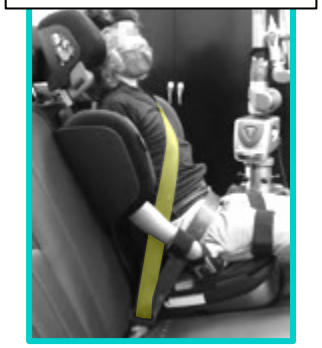
07-Low
Gap Length = 25.1 mm
Max Gap = 13.2 mm



08-Low
Gap Length = 0.0 mm
Max Gap = 11.3 mm



09-LB
Gap Length = 4.9 mm
Max Gap = 14.0 mm

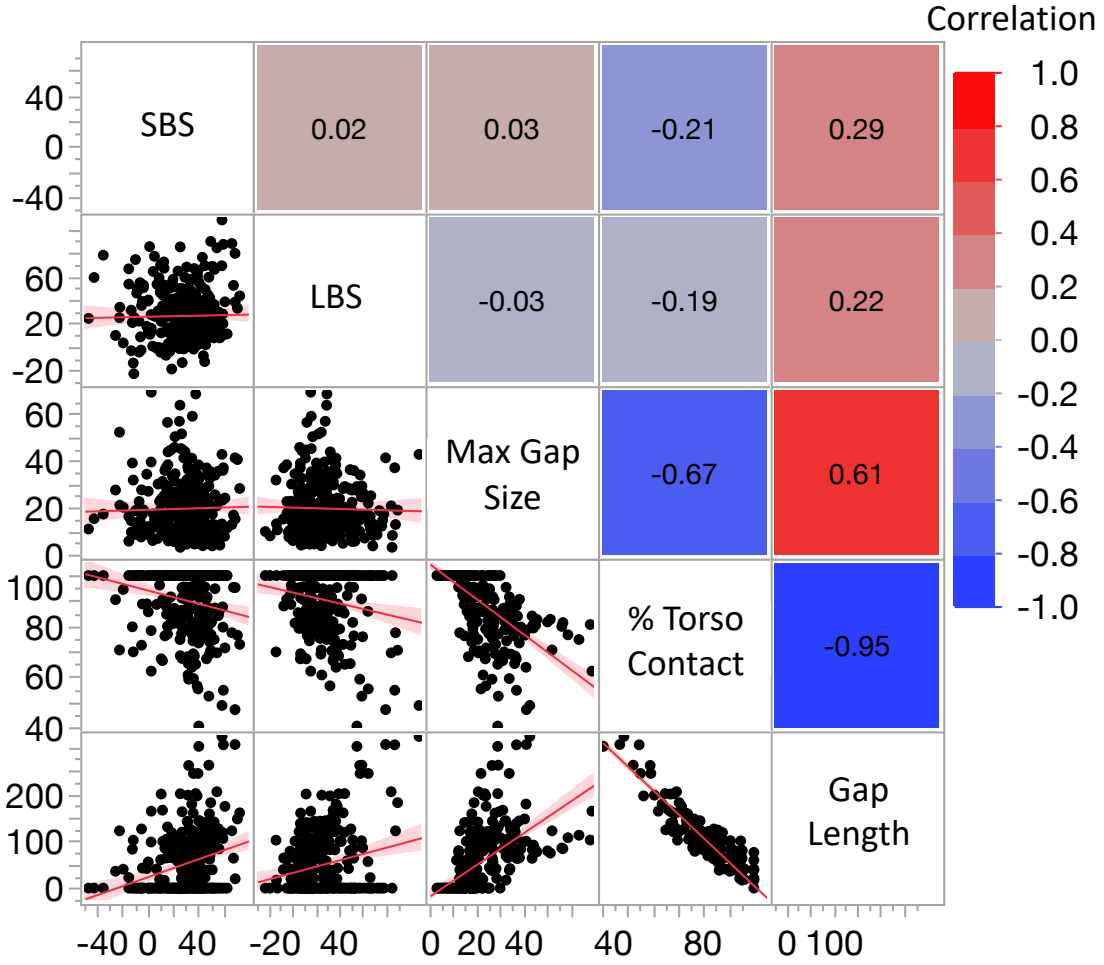


- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

RESULTS: BELT FIT AND BELT GAP

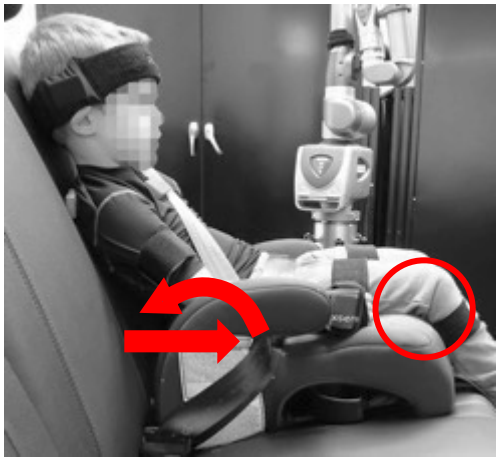
Pearson Correlations

- Belt Gap Metrics
  - Moderate (0.61) to strong (0.95) correlations
- SBS and LBS
  - Weak correlation (0.02)
- SBS, LBS and Belt Gap
  - Weak correlations (0.03–0.22)
- ***Different booster design parameters influence belt fit and belt gap outcomes***



- Baker, G. H., Mansfield, J. A., Hunter, R. L., & Bolte IV, J. H. (2021). Evaluation of static belt fit and belt torso contact for children on belt-positioning booster seats. *Traffic Injury Prevention*, 1-6.

DISCUSSION



- **Some children slouched on LB and Low boosters**
  - More forward pelvis (ASIS) positions
  - More reclined pelvis orientation
- **Slouched postures can occur** because children have shorter thigh lengths and want to **comfortably bend their knees**
  - Some LB designs have long seat lengths
  - Low-Profile designs don't boost the child's seated height → children essentially seated directly on the vehicle seat

LB 

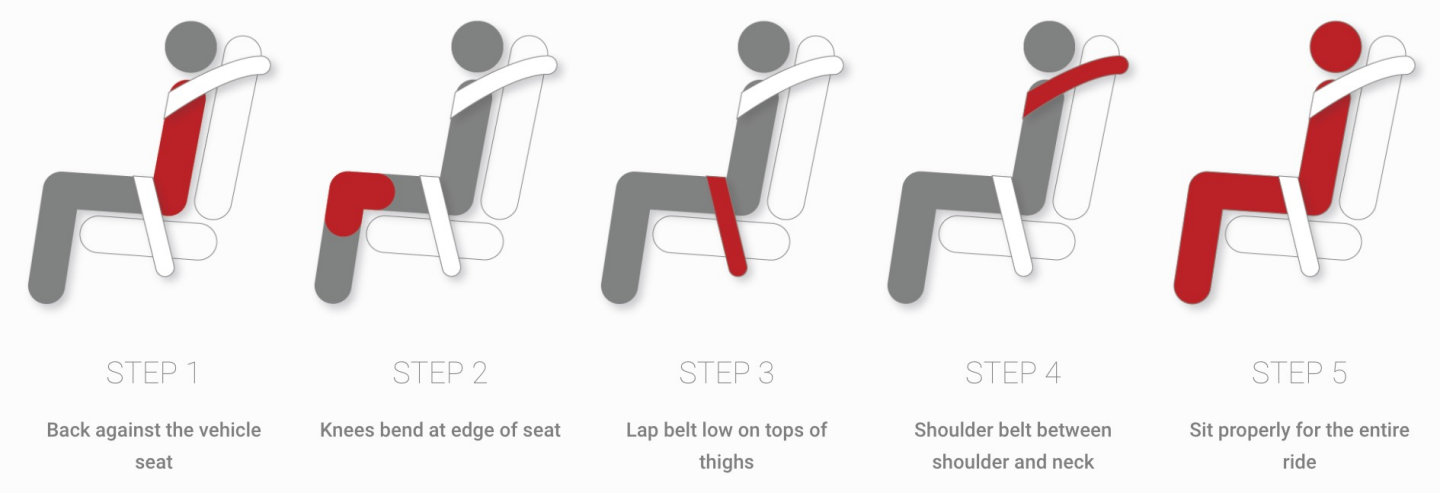
Low 

- **Slouched postures may contribute to suboptimal crash outcomes**
  [Beck 2014; Maheshwari 2020; Izumiyama 2018]

- Beck B, Brown J, Bilston LE. Assessment of Vehicle and Restraint Design Changes for Mitigating Rear Seat Occupant Injuries. Traffic Inj Prev. 2014;15(7):711-719.
- Izumiyama T, Nishida N, Iwanaga H, et al. The analysis of an individual difference in human skeletal alignment in seated posture and occupant behavior using HBMs. Conf Proc Int Res Counc Biomech Inj IRCOBI. 2018;2018-Septe:549-560.
- Maheshwari J, Sarfare S, et al. Pediatric occupant human body model kinematic and kinetic response variation to changes in seating posture in simulated frontal impacts–with and without automatic emergency braking. Traffic Inj Prev. 2020;21(S1):S49-S53.

DISCUSSION

- **The Five Step Test**
  - Recommended for children graduating from boosters to the seatbelt alone



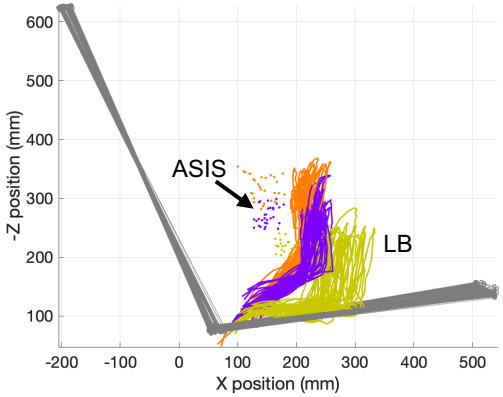
[Buckle Up With Brutus, 2018]

- Making sure this is true for children on boosters too ***may help to prevent and reduce slouched postures***

DISCUSSION

- **SBS within similar range for most booster designs**
  - LB booster with inboard SBS → over armrest routing
    - May increase likelihood of child misusing shoulder belt due to irritation [Vesentini et al. 2007; O'Neil et al. 2009]
  - LB booser with outboard SBS → flexible SB guide
    - May increase likelihood of belt slip-off during maneuvers or crashes

- **LB/Low boosters with inferior/distal LBS**
  - Backless design + rear ASIS position + lap belt guides → pull belt forward
    - May allow more forward pelvis motion before engagement with lap belt [Reed et al. 2008; Klinich et al. 2020]
  - May be particularly poor if combined with pre-crash slouching



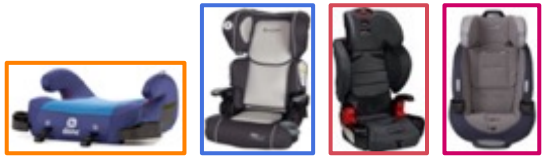
• O'Neil, J., Daniels, D. M., Talty, J. L. & Bull, M. J. Seat belt misuse among children transported in belt-positioning booster seats. Accid. Anal. Prev. 41, 425–429 (2009).
• Vesentini, L. & Willems, B. Premature graduation of children in child restraint systems: An observational study. Accid. Anal. Prev. 39, 867–872 (2007).
• Reed MP, et al. Evaluation of the static belt fit provided by belt-positioning booster seats. Accident Analysis and Prevention, 2009, 41:598–607.
• Klinich KD, Jones MH, et al. Investigation of Potential Design and Performance Criteria for Booster Seats Through Volunteer and Dynamic Testing. Technical Report, 2020, DOT HS 812 919.

DISCUSSION

- Small/short gap achieved by variety of booster types
  - 3in1, Comb, HB, LB, Other

- Smallest/shortest gap: booster without direct belt routing near buckle

- Greatest/longest gap: belt guides pull belt forward away from torso



DISCUSSION

- **Gap metric outcomes are related**
  - Greater Maximum Gap Size → Longer Gap Length
- **No strong correlations between belt gap and belt fit metrics**
  - Different booster design features influencing belt fit and gap outcomes
- **Boosters display different combinations of belt fit and belt gap metrics**
  - Dynamic evaluation required

LIMITATIONS

- 10 boosters not representative of all designs
  - Other belt routings may influence belt fit and gap outcomes
- Volunteers may not represent all booster users
  - Misuse (younger/smaller children)
- Static evaluation only
  - Boosters may have differing abilities in maintaining initial belt fit during dynamic events
- Children encouraged to maintain “standard” posture
  - Does not represent range of occupant postures/behaviors during driving

ACKNOWLEDGEMENTS

The child volunteers and their families

CChIPS
Center for Child Injury Prevention Studies

Children's Hospital of Philadelphia
RESEARCH INSTITUTE

THE OHIO STATE UNIVERSITY
WEXNER MEDICAL CENTER

GR101045

Faculty, Staff, and Students of the IBRC

Julie Mansfield, Randee Hunter, John H. Bolte IV, Jiho Chung, Justin Dannemiller, Reagan Di Iorio, Yun Seok Kang, Caroline Karczewski, Alyssa Noe, Yadetsie Zaragoza-Rivera, Aubrie Sanchez, Akshara Sreedhar, Angela Tesny, Molly Tillis, Nathaniel Williams

Jiaho Ping of the Ohio State University

The authors would like to acknowledge the National Science Foundation (NSF) Center for Child Injury Prevention Studies at the Children's Hospital of Philadelphia (CHOP) and the Ohio State University (OSU) for sponsoring this study and its Industry Advisory Board (IAB) members for their support, valuable input and advice. The views presented are those of the authors and not necessarily the views of CHOP, OSU, the NSF, or the IAB members.

CChIPS | Center for Child Injury Prevention Studies

EVALUATION OF POSTURE AND BELT FIT FOR BOOSTER-SEATED CHILDREN

Gretchen H. Baker, PhD

Injury Biomechanics Research Center, Ohio State University | Gretchen.Baker@osumc.edu

Child Occupant Protection: Latest Knowledge and Future Opportunities | 21 September 2022

Children's Hospital of Philadelphia RESEARCH INSTITUTE

THE OHIO STATE UNIVERSITY WEXNER MEDICAL CENTER