Influence of Clavicle Movement and Chest Clip Position on Thorax Displacement in Young Children

Saskia D. Richter[1], Karolina Ostapkiewicz[1], John Borstad[2], John H. Bolte IV[1], Laura C. Boucher[1]

[1]Injury Biomechanics Research Center, Division of Anatomy, The Ohio State University
[2]Division of Physical Therapy, The Ohio State University

ABSTRACT

Displacement of the thorax and head are directly related to displacement of the shoulder girdle. In the event of a frontal crash, the child will interact with the CRS harness, forcing the clavicles posterior, along with the entire shoulder girdle complex. Currently, the 3-year-old ATD shoulder complex may not fully capture this movement. By understanding how the shoulder and clavicle move, we can better predict the overall effect of impacts on the thorax, cervical spine, and head. To our knowledge there have been no studies that have quantified anterior-posterior clavicular displacement of 2-4 year old children. This study seeks to understand the role of chest clip position and harness tightness on clavicular displacement in 2-4 year old children.

Data was collected from 23 children, 2-4 years old, after obtaining IRB approval and parental consent. Anthropometry measurements were taken and clavicular motion was captured using an electromagnetic tracking system (trakSTAR, Ascension, Shelburne, VT). Surface electrodes were placed on the: sternum, spinous process of T1, distal end of the right clavicle, right acromion process (of scapula), and right deltoid tubercle (of humerus). Anatomical segments were digitized using MotionMonitor (Innovate Sports Training, Inc., Chicago, IL). Following instrumentation, anterior and posterior passive excursion of the shoulder was measured while the child was holding onto a hand-strap connected to a hand-held digital dynamometer (Baseline Instruments, White Plains, NY). Children were passively pulled into shoulder flexion and extension with 5-10 pounds of force. Each measurement was repeated twice. Children were placed in a 5-point CRS (Evenflo Triumph, Evenflo Company Inc.). Clavicular displacement was measured using 4 conditions: proper harness tightness and chest clip position, proper harness tightness with low chest clip position, loose harness with proper chest clip position, and loose harness with low chest clip position. Loose harness conditions were standardized on each child using a 6.3cm block. Each CRS testing condition was repeated 3 times. Anthropometry measurements and CRS scenarios were repeated using a 3 year-old ATD for comparison.

Basic anthropometry was collected. Anterior-posterior displacement (x-axis) of the clavicle was calculated relative to the sternum in all CRS conditions. Displacement x conditions (CRS-Normal, CRS-Low, CRS Lose-Normal, CRS Loose-Low) were analyzed using MatLab (The MathWorks, Natick, MA). Volunteer data was compared to the 3 year-old ATD. A total of 23 volunteers (2-4 years-old) and one ATD were tested. Volunteers were significantly smaller across most anthropometric measurements. Maximum anterior and posterior displacement of the clavicle and anterior maximum displacement of T1 were significantly greater in the volunteer population. The effect of chest clip and harness tightness on clavicular movement was also analyzed, showing that the location of the chest clip was a greater factor on anterior displacement of the thorax compared to harness tightness.

These data may benefit future 3 year-old ATD shoulder designs or computer models. Understanding clavicular movement relative to chest clip position will help to better predict the effect of impacts on thorax, cervical spine, and head excursion in motor vehicle crashes.

INTRODUCTION

Motor vehicle crashes (MVCs) are the number one cause of pediatric trauma and fatalities.[1] A search of the National Highway Traffic and Safety Administration database yields 4,062 cases of children, between the ages of 0-4 years-old, injured in MVCs. Of these, injuries to the upper limb, thorax, neck, face, and head account for a total of 54% of cases. These areas are especially vulnerable during frontal impacts, which account for 46% of cases.[2]

Upon impact, the head, cervical spine, and thorax are dependent on the response of the shoulder girdle complex.[3] The shoulder girdle is comprised of several joints: the sternoclavicular (SC), acromioclavicular (AC), and glenohumeral (GH) joints whereas, the shoulder joint is only between the humerus and the scapula (GH joint). By understanding how the shoulder complex (humerus, scapula, and clavicle) moves, we can better predict the overall effect of impacts on the thorax, cervical spine, and head.

While research has been conducted to understand the biomechanical differences in the GH and ST joints between adults and children,[3,4,5] there is minimal research focusing on the AC and SC joints. Specifically, no research has been found that investigates the anterior-posterior motion of the shoulder girdle in the pediatric population. Yet, this is a critical motion to understand for a child positioned in a child restraint system (CRS), as impact forces must travel through the clavicle, a key link in this chain, which will affect head and neck response.

In a CRS, the shoulder harness should rest along the middle 1/3 of the clavicles.[6] During a frontal crash, the harness prevents anterior displacement of the thorax, forcing the clavicles in a posterior direction. This motion directly impacts the total amount of head excursion. Harness tightness and chest clip position play an important role in preventing excessive anterior thorax displacement.[7] Yet, harness tightness and chest clip position are among the most common mistakes made by the caregiver.[6,7,8] For example, Klinch et al. found that harness tightness was inadequate in 48% of installations and clip position was incorrect in 47%.[6]

It is well documented in the literature that improper CRS installation and usage is a risk factor for injury,[6,7,8] yet a true understanding of a child's response in a CRS is unreliable if the ATD used for testing lacks biofidelity. In general, ATD shoulder girdle complexes are stiff and non-biofidelic.[9] This is true for the pediatric ATD as well, as many of their segments are constructed from scaled adult data, implying children will react and move in a manner similar to adults.[10] To improve future child ATDs and computer model development, we must have a better understanding of how the pediatric shoulder girdle complex responds in various conditions.

The primary goal of this research was to investigate the anterior-posterior displacement of the shoulder girdle in 2-4 year-old children. The role of CRS harness tightness and chest clip position was also analyzed for its influence on displacement of the shoulder girdle and thorax. Data and results collected from this study may be used to better understand the biomechanics of pediatric clavicular movement, which may help to develop a more biofidelic ATD shoulder girdle and allow for more accurate computer models.

METHODS

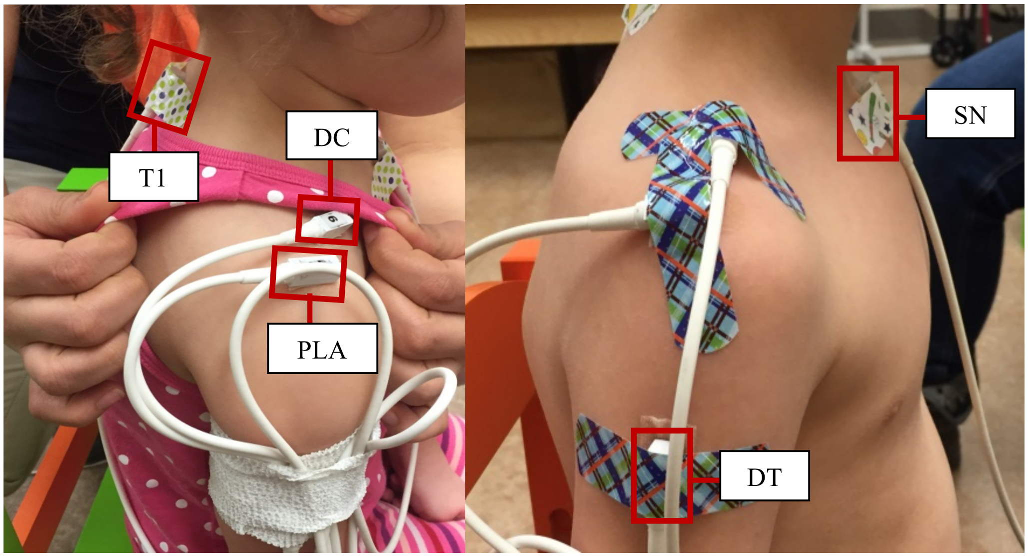
Twenty-three pediatric volunteers between the ages of 2 to 4 years old were recruited, who had no history of shoulder, clavicle, or cervical spine injury. Data collection began following Institutional Review Board approval (*IRB protocol #2015H0258*) and a signed parental consent for each participant. All volunteer testing conditions are listed in Table 1 and are described in detail below.

Table 1. Volunteer Test Matrix

Measuring	Test	Trials	Force
Distal Clavicle Displacement (relative to T1)	Anterior Pull	2	10 lbs
	Posterior Pull	2	10 lbs
	CRS (4 conditions)	3 (per condition) 12 total	Active
T1 Displacement	CRS (4 conditions)	3 (per condition) 12 total	Active

Basic anthropometry measurements were taken of each volunteer using standard clinical methods (*Rosscraft Centurion Kit, Rosscraft Innovations, Vancouver, Canada*). All measurements were taken with the child in a seated position. Measurements included: height, weight, shoulder width, acromial width, clavicular length, humeral length, bicep circumference, chest circumference, and seated height.

Shoulder girdle motion was captured using trakSTAR, an electromagnetic tracking system *(trakSTAR, Ascension, Shelburne, VT*). Five electromagnetic sensors were attached to the child cutaneously over boney landmarks as recommended by the International Society of Biomechanics[11], which included the sternal notch, T1, distal clavicle, posterior-lateral acromion (PLA), and deltoid tuberosity (Figure 1). Participants' skin was cleaned and prepped using an alcohol wipe, followed by an adhesive tape directly on the participants' skin under each sensor location. The sensors were then secured to adhesive tape located on the skin with an additional piece of double-sided tape. Band-Aids were then placed over the sensors to help further secure them (Figure 1b). Sensor wires were grouped and loosely connected to volunteers upper arm to prevent sensor displacement due to movement. Anatomical segments were digitized using MotionMonitor *(Innovate Sports Training, Inc., Chicago, IL)* and reference points were made for each sensor. To assure the participant did not move during digitization, they were seated in a child-size wooden chair and with parental permission were allowed to watch Netflix Kids *(Netflix, Los Gatos, CA)*. Researchers had no difficulty digitizing each segment once the child was preoccupied.



a. medial view **b**. medial view

Figure 1. Volunteer Sensor Set-up (**a)** T1, distal clavicle (DC), and posterior lateral acromion (PLA) (**b)** deltoid tuberosity (DT), and sternal notch (SN).

Maximum Clavicular Excursion Measurements

Following instrumentation and digitization, volunteers were guided through two passive movements, a forward arm pull and a backward arm pull, to identify maximum clavicular excursion in both anterior and posterior directions. Each motion was performed twice. All testing was conducted with participants seated in a wooden children's chair. Each pull was standardized, using 5-10lbs of force with a hand-held digital dynamometer *(Baseline Instruments, White Plains, NY)*. To allow for passive movement of the upper extremity, children were instructed to grasp onto a hand-strap connected to the dynamometer and to relax while the researcher pulled their arms into position. Demonstrations of each task were performed for the child prior to them completing a task.

Forward pulls were conducted with the children sitting backward in a child-sized chair, which allowed the backrest to function as a restraint to stabilize the thorax, while permitting clavicle displacement during the task. Volunteers grasped a single handle with both hands. (Figure 2). Researchers were able to passively flex the shoulder and pull the upper extremity anteriorly, while pulling on the dynamometer attached to the hand-strap. End range of motion was held for three seconds with 5-10lbs of force. Arms were brought back to neutral before the second trial began.

a) anterior pull b) posterior pull

Figure 2. Anterior pull (a) and posterior pull (b) for maximum clavicle displacement.

Backward pulls were conducted with children sitting forward, with a two-handled hand strap pulled up to their elbows. Children were instructed to, "*put the handles on like coat sleeves"*. Researchers then passively extended the shoulders over the chair back and pulled the upper extremity posteriorly. End ranges of motion were held for three seconds at 5-10lbs of force. Arms were brought back to neutral before the second trial began.

CRS Measurements

Children were then placed in a five-point CRS *(Evenflo Triumph, Evenflo Company Inc., Miamisburg, OH)*. Participants were guided through active forward motions. To reproduce the same movement with each child, a basic game was developed. Participants were asked to lean forward, and attempt to hit a ball with their head. They had three attempts to hit the ball, coming back to the starting position between each attempt. Children were instructed to move only their head (*"hands in your lap")* to prevent excessive upper extremity motion. The same game was repeated under four testing conditions: proper harness tightness and chest clip position, proper harness tightness with low chest clip position, loose harness with proper chest clip position, and loose harness with low chest clip position. Loose harness conditions were standardized on each volunteer using a 6.3cm block (Figure 3).

a. b. c. d.

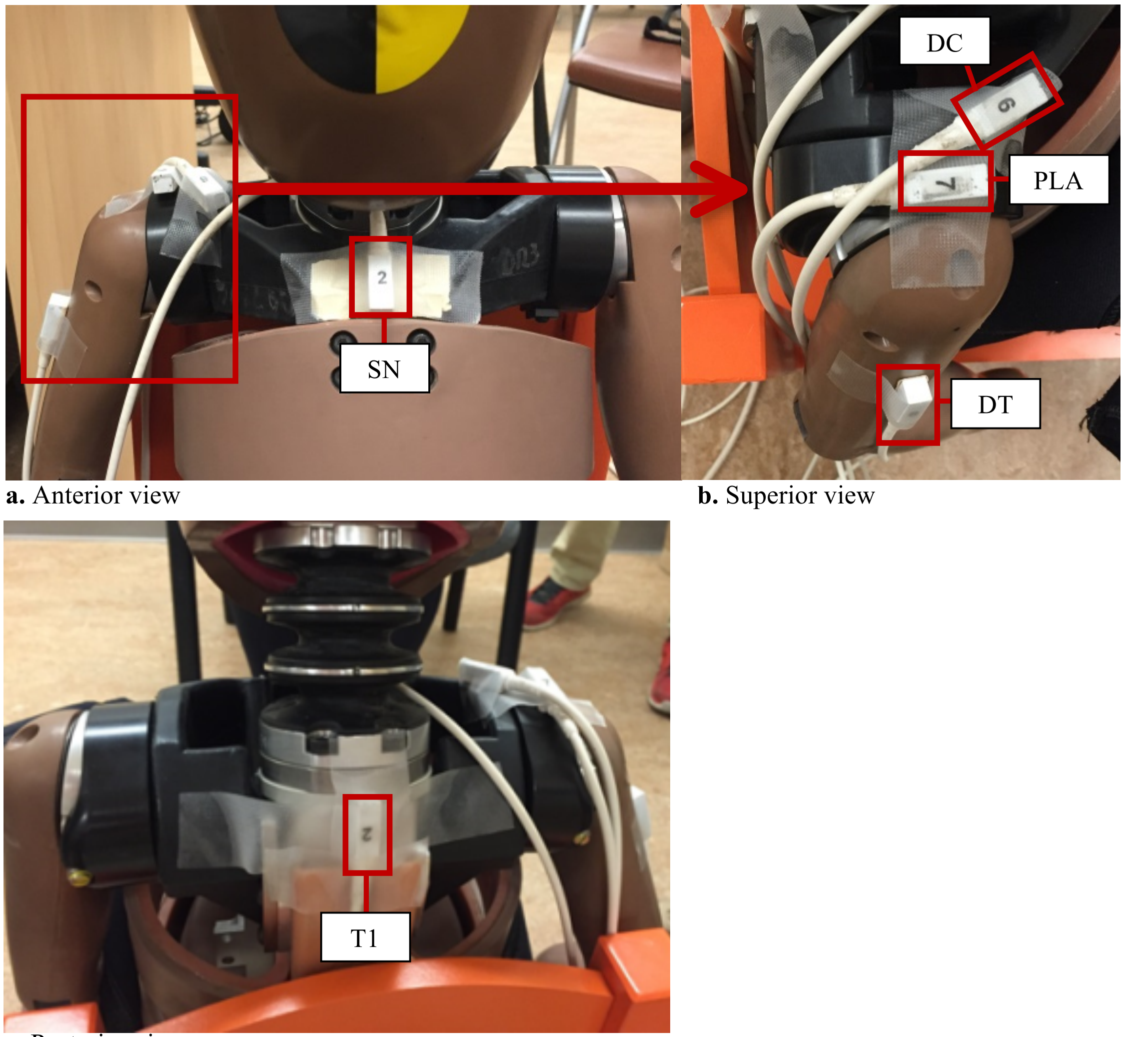
Figure 3. CRS chest clip position and harness tightness procedure. **(a)** Normal chest clip, **(b)** Low chest clip, **(c)** Spacer for loose harness, **(d)** Loose harness

ATD Testing

All testing conditions (passive pulls and CRS) were completed on a Q3s ATD (*Humanetics, Plymouth, MI)* for comparison; refer to Table 2 for test conditions. Sensors were attached the surface of the ATD using a double sided adhesive tape. While the ATD does not have anatomical locations identical to a live subject, sensors were placed in locations considered "anatomically comparable" (Figure 4).

Table 2. ATD Test Matrix

Measuring	Test	Trials (per force)	Rest Period	Force
Distal Clavicle Displacement (relative to T1)	Anterior Pull	2	1 min	5, 10, 20, 30 lbs
	Posterior Pull	2	1 min	5, 10, 20, 30 lbs
	CRS (4 conditions)	3 (per condition) 28 total	1 min	5, 10, 20, 30 lbs
T1 Displacement	CRS (4 conditions)	3 (per condition) 28 total	1 min	5, 10, 20, 30 lbs



a. Anterior view

b. Superior view

c. Posterior view

Figure 4. Sensor placement for ATD. **(a)** sternal notch (SN) **(b)** distal clavicle (DC), posterior lateral acromion (PLA), and deltoid tuberosity (DT). **(c)** T1.

Anterior and posterior pulls were done with the ATD seated in the same wooden chair as participants. Handle straps were secured to the ATD hands using a non-adhesive wrap**.** Both anterior and posterior pulls were tested at four different dynamometer force levels: 5, 10, 20, and 30lbs of force. Rest periods of one minute were included between each trial.

The ATD was then moved to the CRS and fastened under the same parameters as the volunteers. To reproduce anterior movement of the head and thorax, handle straps were secured to the ATD's head. Each testing condition was repeated with dynamometer pulls at four different force levels: 5, 10, 20, and 30lbs of force. Rest periods of one minute were included between each trial, to allow for materials to return to initial conditions.

Data and Statistical Analysis

Anterior-posterior displacement (x-axis) of the distal clavicle relative to T1 was calculated in all testing conditions. Additionally, displacement (x-axis) of T1 was calculated separately. For each testing condition, volunteer and the ATD motion was analyzed using MatLab (*The MathWorks, Natick, MA*). Refer to Tables 1 and 2 for testing conditions. Data was collected at a sampling rate of 80Hz and was filtered through MatLab.

Raw data (x-axis) was extracted from MotionMonitor and imported in to MatLab. Custom scripts were created to plot and visually evaluate individual subject and ATD data. Excessive noise and sensor malfunction resulted in some of the data being excluded from further analysis. Final graphs provided baselines for each anterior pull, posterior pull, and all four CRS conditions. Numeric data was compared to graphs for consistency.

To analyze anterior and posterior pulls, recorded maximum displacement of T1 and the distal clavicle was found within MatLab. Relative zero was found and a relative maximum was calculated (recorded maximum – relative zero). Relative maximums between trials were compared, and the larger used for analysis. Data from the ATD was collected in a similar manner, but only data from 10 and 30lbs of force were used for analysis. These were chosen as they represent the equivalent force (10lbs of force) applied to volunteers, and the maximum force (30lbs of force) conducted on the ATD.

Each of the four CRS trials were analyzed in a similar manner. For each volunteer, maximum displacement (recorded maximum – relative zero) was taken of T1 and the distal clavicle. Similar methods were used to collect ATD data. For CRS ATD trials, only 20 and 30lbs of force were analyzed due to immeasurable displacements at 5 and 10lbs of force. Statistics were conducted in StataSE 12.0 *(Stata, College Station, TX*). Analysis included, one-way ANOVA, Scheefe's post hoc tests, and Student's T-test. P-values were set to .05.

RESULTS

Anthropometrics

Twenty-three pediatric volunteers, between the ages of 2-4 years old participated. Subject demographics and anthropometry measurements are presented in Table 3, Figure 5. A significant difference between the ATD and volunteer anthropometry in shoulder width ($t(22) = -3.02$, $p=.01$), AC width ($t(22) = 6.24$, $p<.001$), clavicular length ($t(22) = 7.55$, $p<.001$), humerus length ($t(22) = -6.48$, $p<.001$), and arm circumference ($t(22) = -1.72$, $p=.03$) was found (Appendix A). All twenty-three volunteers were included in the demographic and anthropometry analyses. Twenty-one volunteers were included in the remaining analysis due to sensor error or an inability to complete the task. Depending on the testing condition, valid data ranged from 17 to 21 subjects (ForwardPull = 20, Backward Pull = 21, PropHarnNorm = 18, PropHarnLow = 20, LsHarnNorm = 17, LsHarnLow = 19).

Table 3. Subject Demographics

	N	Age (years)	Mass (kg)	Height (cm)
Volunteers	23	3.4 ±0.9	16.1 ±3.5	97.5 ±9.2
Q3s ATD	1	3	14.2	------

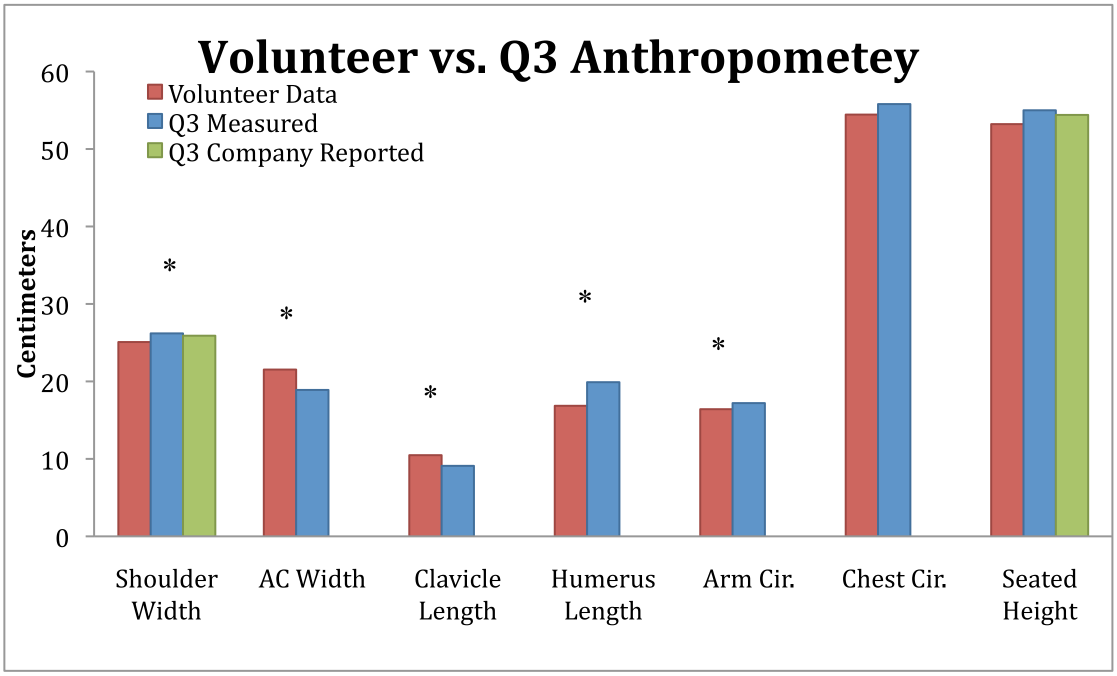


Figure 5. Volunteer vs. Q3s Anthropometry. * = significance; p<.05.

Maximum Clavicular Excursion Results

Anterior and posterior pull trials were quantified and compared and an overall max displacement was determined for each subject. Max relative displacement between T1 and the distal clavicle during the forward pull was 1.98cm $\pm$ .99 (n=21), while during the backwards pull was 3.19 $\pm$ 1.50 (n=20). Volunteer data was then compared to the Q3s ATD. The ATD has significantly less displacement compared to volunteers (Table 4).

Table 4. Displacement of T1 to distal clavicle (DC)

T1 to DC Displacement (cm)	Volunteer	ATD 10lb	t	p-value	ATD 30lb	t	p-value
Anterior	1.98	1.03	4.44	<.001	1.38	2.81	.01
Posterior	3.19	.45	8.13	<.001	.39	8.31	<.001

Table 4. Volunteer vs ATD anterior and posterior pull. T-Test. Significance set to p<.05.

Data from all of the CRS conditions was quantified and analyzed with MatLab. Both relative distal clavicle to T1 displacement and isolated T1 displacement was analyzed. Significant differences were found in T1 displacement over CRS testing conditions (PropHarnNorm, PropHarnLow, LsHarnNorm, LsHarnLow).

An analysis of variance (ANOVA) was performed for the four CRS testing conditions. Overall significance was found, $F(3,75) = 45.91$, $p<.001$. Scheffe's post hoc comparison was used to compare groups of unequal sample size. Significant differences between the control (PropHarnNorm) and experimental groups PropHarnLow and LsHarnNorm were found. However, a loose harness with a normal clip position was not significantly different than a proper harness with a low clip position ($p=.729$) (Table 5).

Table 5. Displacement of T1

(T1 Displacement cm)	PropHarnNorm	PropHarnLow	LsHarnNorm
ProprHarnLow	.013	--------------------	-----------------
LsHarnNorm	.164	.729	-----------------
LsHarnLow	<.001	<.001	<.001

Table 5. During CRS conditions. Scheffe's. Significance set to p<.05

Relative displacement between T1 and distal clavicle showed similar ANOVA results, $F(3,71) = 9.66$, $p< .001$. Interestingly group comparisons found significance only in LsHarnLow conditions (Table 6).

Table 6. Displacement of T1 and the distal clavicle (DC)

T1 to DC Displacement (cm)	PropHarnNorm	PropHanLow	LsHarnNorm
ProprHarnLow	.311	--------------------	-----------------
LsHarnNorm	.999	.389	-----------------
LsHarnLow	<.001	.049	<.001

Table 6. During CRS conditions. Scheffe's. Significance set to p<.05

Student's T-Tests (two-way) were conducted to compare volunteer and ATD values. The ATD moved significantly less ($p<.001$) than volunteers at 20lbs during PropHarnNorm, PropHarnLow, and LsHarnLow the ATD moved significantly less than volunteers. All four testing conditions were significantly different at 30lbs, $p<.001$ (Tables 7 and 8).

Table 7. Displacement of T1.

T1 Displacement (cm)	Volunteer Mean	ATD 20lbs	t	p-value	ATD 30lbs	t	p-value
PropHarnNorm	4.08	1.95	6.30	<.001	2.59	4.41	<.001
PropHarnLow	6.58	2.16	9.25	<.001	3.01	7.48	<.001
LsHarnNorm	5.76	5.3	.91	.38	7.99	-4.30	<.001

LsHarnLow	11.98	6.86	8.30	<.001	8.83	5.11	<.001

Table 7. Volunteers' vs ATD during CRS conditions. T-Test. Significance set to p<.05.

Table 8. Displacement of T1 to DC

T1 to DC Displacement (cm)	Volunteer Mean	ATD 20lbs	t	p-value	ATD 30lbs	t	p-value
PropHarnNorm	2.87	.96	8.78	.000	1.132	7.99	.000
PropHarnLow	3.64	1.14	9.58	.000	1.34	8.82	.000
LsHarnNorm	2.89	1.90	3.71	.002	1.993	3.36	.004
LsHarnLow	4.51	1.76	10.07	.000	1.82	9.85	.000

Table 8. During CRS conditions. Volunteers' vs ATD. T-Test. Significance set to p<.05.

DISCUSSION

Through this study the anterior-posterior displacement of the shoulder girdle for 2-4 year-old children was analyzed. Specifically, the motion of the distal clavicle, T1, and their relationship under various CRS conditions was studied. All results were compared to data collected from an ATD under similar testing conditions. This study found the ATD should girdle and thorax moves less in the anterior-posterior direction then age-matched volunteers. Also, CRS conditions (harness tightness and chest clip position), play a role in total displacement for both volunteers and the ATD.

Basic anthropometric measurements provide data on differences between the Q3s ATD and actual 2-4 year olds. While height and weight were comparable, other measurements differed significantly. The ATD is made to be representative the 50^{th} percentile 3 year-old, this is concerning, especially when determining how each body segment will react to the CRS, and overall, in a crash scenario. It is important to note that not all anatomical landmarks are represented on the ATD, thus some anatomical locations were estimated.

Both anterior and posterior clavicular displacements, relative to T1, were significantly smaller in the ATD compared to the volunteers. This lack of motion between the ATD shoulder girdle and the volunteers is concerning. Without realistic motion of the shoulder girdle, the ATD cannot accurately estimate secondary thorax, cervical spine, and head movement. More so, the ATD would potentially underrepresent the effects of the CRS on anterior and posterior clavicular motion upon impact.

As predicted a loose harness with a low chest clip allowed for the greatest displacement of T1 (volunteers = 11.98cm; ATD = 8.83cm). Overall, T1 displacement did not significantly change from normal to when a harness was loose but had the chest clip in the right position (Volunteer PropHarnNorm = 4.08; LsHarnNorm = 5.96; p=.164). Under normal conditions the present study suggests that the chest clip is more important than harness tightness in preventing anterior thorax movement. The same held true when comparing the relative displacement between the distal clavicle and T1. With the chest clip being more important that harness tightness in overall thorax displacement, it is relevant to note that many European CRS models do not include a chest clip. Future research may lead to understanding how those CRS models work to prevent anterior displacement without the added help of a chest clip.

When comparing volunteer and ATD CRS data it was obvious that the ATD moved less, and in many cases was not comparable to the movement produced by volunteers. By not having realistic thorax and clavicular displacement, it becomes difficult to understand the relationship between shoulder girdle, thorax, spine, and head movement as they relate to each other in crash scenarios. As the current ATD model stands, it is far from representing the anterior-posterior movement of the pediatric shoulder girdle. This serves a problem when attempting to model how a child may react to a CRS harness during a frontal or rear crash.

Limitations

A primary limitation to this study is the challenge of using pediatric volunteers. Collection of volunteer pediatric data has long been seen as a barrier. While some volunteers were more cooperative then others, we only had one child refuse to cooperate across all trials. While testing conditions may not have been perfect in each scenario (sensor malfunction, loss of interest form participant, lack of effort from participant, etc.), overall data collected shows repeatability of our methods. The rate of testing must also be acknowledged as a limitation. The passive pulls and active CRS trials were all in the quasi-static range. While this range is safe for the child volunteers, the ATD was designed to be tested at much higher speeds.

CONCLUSION

It is important to realize that children cannot be modeled as scaled down adults. Understanding how the clavicle moves in the anterior and posterior direction will help to design more biofidelic 3 year-old ATDs or computer models. By knowing the anterior-posterior movement capable at the shoulder girdle, researchers will be able to better predict how it will respond during both frontal and rear crashes. This research is especially relevant in measuring the effects of harness tightness and chest clip position on shoulder girdle, thorax, cervical spine, and head movement.

ACKNOWLEDGEMENTS

A sincere thanks to the sponsor of this project, the Center for Child Injury Prevention Studies (CChIPS) and our industry mentors on the project **Eric Dahle**, Evenflo Company Inc.; **Phil Przybylo**, Evenflo Company Inc.; **Jack Jensen**, General Motors Holdings LLC; **Taft Jones**, Graco Children's Products Inc.; **Jerry Wang**, Humanetics Innovative Solutions Inc.; **John Combest**, Nissan Technical Center North America Inc.; **Hiromasa Tanji**, TK Holdings Inc.; **Jason Gainey**, Volkswagen Group of America. Thanks to Dr. Alexandria Borstad for allowing us to conduct subject data collection in her lab and all of the families who volunteered to be a part of this project.

REFERENCES

1. Guice KS, Cassidy LD, Oldham, KT. Traumatic injury and children: a national assessment. *J Trauma*. 2007;63(6):S68-80.
2. National Highway Traffic Safety Administration (NHTSA). National Automotive Sampling System (NASS). *www.nhtsa.gov/nass.* Accessed: May 25th, 2016.
3. Suntay B, Moorhouse K, Bolte J. Characterization of the pediatric shoulder's resistance to lateral loading conditions. *ESV paper*. 2011; Paper#11-0038.
4. Dayanidhi S, Orlin M, Kozin S, Duff S, Karduna A. Scapular kinematics during humeral elevation in adults and children. *Clin Biomech*. 2005; 20:600-606.
5. Hebechian FAP, Fornasari GG, Sacramento LS, Camargo PR. Differences in scapular kinematics and scapulohumeral rhythm during elevation and lowering of the arm between typical children and healthy adults. *J. Electromyography and Kinesiology*. 2014; 24:78-83.
6. Klinich KD, Manary MA, Flannagan CA, et. al. Effects of child restraint system features on installation errors. *J. of Applied Ergonomics.* 2014;45:270-277.
7. National Highway Traffic Safety Administration. National Child Restraint Use Special Study. *Traffic Safety Facts – Research Note*. 2012; DOT HS 811 679
8. Koppel S, Charlton JL. Child restraint system misuse and/or inappropriate use in Australia. *Traffic Inj Prev.* 2009;10(3):302-7.
9. Shaw G, Lessley D, Crandall J, et al. Response comparison for the Hybrid III, THOR mod kit with SD-3 shoulder, and PMHS in a simulated frontal crash. *ESV paper*. 2013. Paper#13-0130.
10. van Ratingen MR, Twisk D, Schrooten M, Beusenberg MC. Biomechanically based design and performance targets for a 3-year old child crash dummy for frontal and side impact. *Society of Automotive Engineers*. 1997.
11. Wu G, VanderHelm FCT, Veeger HEJ, et al. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *J Biomech*. 2005;38(5):981-992. doi:10.1016/j.jbiomech.2004.05.042.

Appendix A

Volunteer vs. Q3s Anthrompometry

Anthropometrics (cm)	**Volunteer**	**ATD**	**t**	**p-value**
Shoulder Width	25.08	26.2	-3.02	.01
AC Width	21.53	18.9	6.24	<.001
Clavicle Length	10.47	9.1	7.552	<.001
Humerus Length	16.85	19.9	-6.48	<.001
Arm Circumference	16.41	17.2	-2.29	.03
Chest Circumference	54.44	55.8	-1.72	.09
Seated Height	53.21	55	-1.76	.09

Student's T-test, $p < .05$