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Evaluation of Harness Tightening Procedures for Child Restraint System (CRS) Sled Testing

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Abstract

Sled testing procedures should reflect a rigorous level of repeatability across trials and reproducibility across testing facilities. Currently, different testing facilities use various methods to set the harness tension for child restraint system (CRS) sled tests. The objective of this study is to identify which harness tightening procedure(s) produce tensions within a reasonable target range while showing adequate reproducibility, repeatability, and ease-of-use. Five harness tightening procedures were selected: A) FMVSS 213 procedure, B) a 3-prong tension gauge, C) ECE R44/R129 procedure, D) two finger method, and E) pinch test. Two CRS models were instrumented with a tension load cell in the harness system. Seven sled room operators were recruited to perform each of the five harness tightening procedures for ten repetitions apiece on both instrumented CRS using a Hybrid III 3-year-old. The static harness tension measured by the load cell was recorded after each procedure was completed. Data were analyzed for mean, variance, reproducibility, and repeatability. Operator feedback surveys were used to quantify ease-of-use.

The ECE R44/R129 procedure produced harness tensions which were quite low. The two finger procedure produced the highest tensions while the 3-prong tension gauge, pinch test, and FMVSS 213 procedures produced mid-level tensions. Poor repeatability was apparent for all five harness tightening procedures. The FMVSS 213 method ranked lowest for ease-of-use. Operators preferred using the 3-prong gauge, two finger method, and pinch test.

The load cell readings were sensitive to the order and direction in which the operators adjusted the harness components. High amounts of friction within the harness might prevent it from acting as a homogeneous, continuous system. Sequential tightening of the various sections of harness and/or monitoring the tension at multiple locations might be valuable.

Introduction

The repeatability and reproducibility of dynamic sled tests are critical to advancement in the child passenger safety field. Consistent setup procedures allow child restraint system (CRS) manufacturers to analyze the sensitivity of occupant outcomes to intended design changes with minimal noise introduced by variations between setups. The pre-test tension of the five-point harness is a potential source of variability which has not been thoroughly evaluated.

The five-point harness secures the anthropomorphic test device (ATD) into the CRS. Dynamic sled testing analyses show that differences in pre-test harness tension can produce significant differences in kinematic and kinetic outcomes, especially when large amounts of slack are present [1, 2]. Improperly tightened harness straps can also result in unfavorable injury outcomes for children in real-world crashes [3, 4, 5]. It is important that the harness tension is tightly controlled in sled testing so that ATD outcomes can be interpreted in terms of real child injury outcomes.

Most CRS testing facilities do not have a validated procedure to ensure that harness tensions are consistent across repeated trials, between operators, and between facilities. Laboratory Test Procedures for Federal Motor Vehicles Safety Standard No. 213 [6] outlines a preferred procedure for verifying harness tightness during regulation testing. However, many test facilities have developed proxy procedures to simplify the process. Some facilities use hand-held tension gauges to guide their work, while others rely on mostly on the experience of the test operator. The goal of this study is to evaluate several different harness tightening procedures to identify which are the most reproducible and repeatable while also considering operator ease-of-use.

Methods

Equipment

A tension load cell (MLP-50, Transducer Techniques, Temecula, CA) was integrated into the harness system of two convertible CRS models (Cosco Apt 40RF and Safety 1st Alpha Elite 65). The harness webbing was pulled through the hip slots to the bottom surface of the CRS and sewn onto eye bolts

FIGURE 1 The load cell was incorporated into the webbing system underneath the seating surface of the CRS.

which were inserted into the load cell. The load cell was wired to a digital output meter (Figure 1).

Detailed images of the load cell are shown in Figure 2.

The full routing of the harness webbing in relation to the load cell is shown in Appendix A.

Each CRS was installed onto a FMVSS 213 bench in forward-facing mode. The version of the bench varied between the four testing sites based on availability. The lower anchor strap and top tether were tensioned to 15 lbs, as measured by the 3-prong seat belt tension gauge (BT3329S, Bosch, Warren, MI).The shoulder slots were set to accommodate a 3-year-old Hybrid III ATD.

Harness Tightening Procedures

Using guidance from several CRS testing facilities, five harness tightening procedures were defined. The instructions for each procedure and accompanying images were printed and presented to each operator before his/her trials.

Procedure A: FMVSS 213 Webbing Tension Pull Device "In child restraints, other than belt-positioning seats, place the appropriate size dummy in the child restraint for testing. Tighten the child restraint belts until a 9 N (2 lbs.) force applied to the webbing at the top of each dummy shoulder and to the pelvic webbing 50 mm (2 inches) on either side of the torso midsagittal plane pulls the webbing 7 mm (1/3 inch) from the dummy. Use the webbing tension pull device shown in Figure 3 or an aluminum rod of sufficient diameter to perform this evaluation." [6]

FIGURE 2 The load cell was centered on the span of webbing (top image) and custom orange plastic spacers were glued to the shell to ensure the load cell did not contact the bottom surface of the CRS (bottom image).

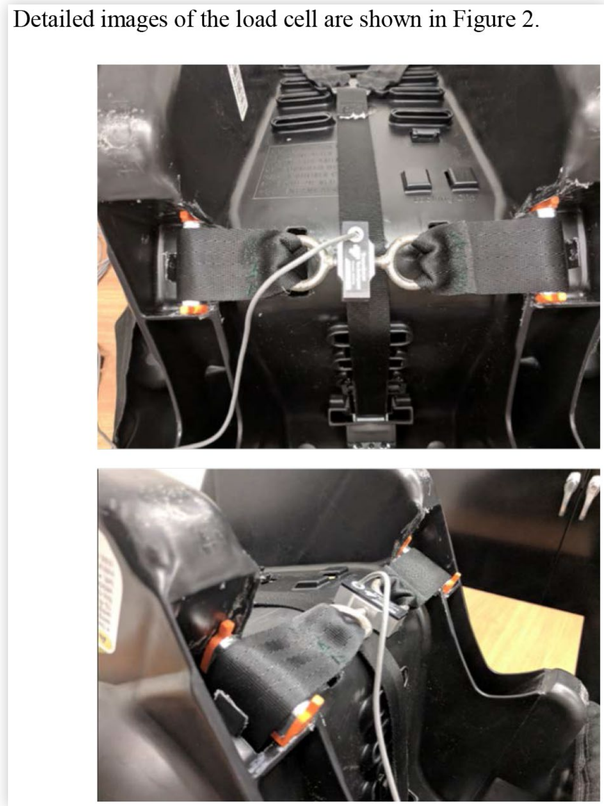
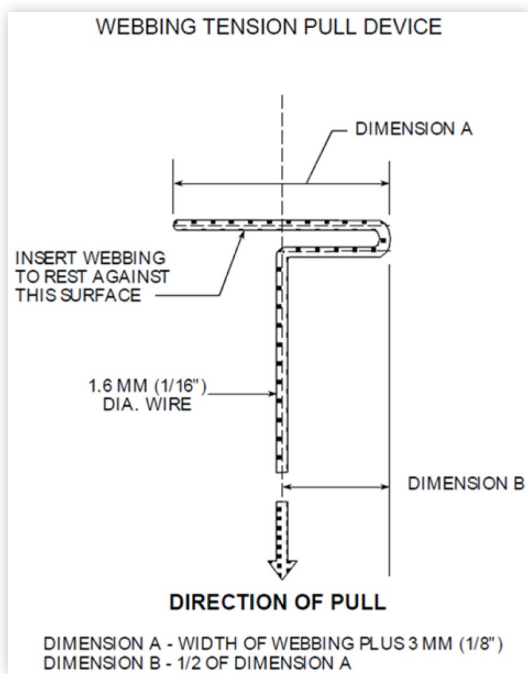


FIGURE 3 FMVSS 213 webbing tension pull device (NHTSA 2014a)



Since the FMVSS 213 webbing tension pull device does not have the capability to measure pulling force, the device was attached to a digital tension gauge (FDX 50, Wagner Instruments, Greenwich, CT). A small ruler was also provided with 7 mm clearly marked.

Procedure B: 3-Prong Tension Gauge "The 3-prong tension gauge shall read between 2-4 lbs (9-18 N) when placed on the harness webbing halfway between the buckle and the chest clip (see yellow stars on photo). Slide the gauge from the outside of the webbing toward the inside for each strap (i.e., from lateral to medial, so that the open end of the gauge is always pointing toward the midline of the ATD). Ensure that the gauge is centered vertically and laterally on the exposed length of webbing."

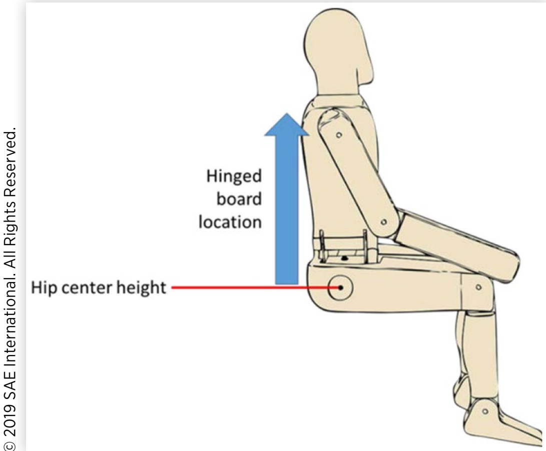
The wording for Procedure B was developed with the input from test engineers from the facilities who participated in this study. The 2-4 lbs target range was originally adapted from the FMVSS seating procedures for belt positioning seats [6]. An image of the 3-prong gauge positioned on the webbing is shown in Appendix B.

Procedure C: ECE R44/R129 Spacer "The dummy shall be placed in the Child Restraint System separate from the seat-back of the chair by a flexible spacer. The spacer shall be 2.5 cm thick and 6 cm wide. It shall have length equal to the shoulder height less the thigh height, both in the sitting position and relevant to the dummy size being tested.... The board should follow as closely as possible the curvature of the chair and its lower end should be at the height of the dummy's hip joint. Adjust the belt in accordance with the manufacturer's instructions, but to a tension of 250 ± 25 N above the adjuster force (the force needed to overcome friction, to start the webbing moving), with a deflection angle of the strap at the adjuster of 45 ± 5°, or alternatively, the angle prescribed by the manufacturer. A digital tension gauge may be used to monitor the tension applied to the adjuster. The spacer shall then be removed and the dummy pushed towards to the seat back using methods similar to those outlined in FMVSS seating procedures (40 lbs force applied to ATD's crotch then thorax, in direction perpendicular to CRS back). Distribute the slack evenly throughout the harness." [7]

An image of the tensioning process for this method is shown in Appendix C.

FIGURE 4 The 3-prong gauge (right) should be used to check the tension at the locations of the stars (left). The gauge should read between 2-4 lbs.

FIGURE 5 The spacer should be positioned at the location shown during R44/R129 procedure.



Procedure D: Two Finger Test "Tighten the harness until two fingers can fit snugly under the webbing near the shoulders, with no additional slack present. Ensure that no slack can be pinched between thumb and index finger."

The wording for Procedure D was developed with the input from test engineers from the facilities who participated in this study.

Procedure E: Pinch Test "Tighten the harness until no webbing can be gathered between the thumb and index finger when the harness is pinched near the shoulder."

The wording for Procedure E was developed from the "pinch test" guideline taught in the National Child Passenger Safety Certification Program [8].

Protocol

The instructions for each of the 5 procedures were printed and presented to each operator in random order. Each operator performed 100 trials total, consisting of 10 repetitions of each of the 5 procedures on 2 CRS models. The ATD was positioned at the beginning of the series according to FMVSS 213 testing procedures [6]. The operator was asked to follow the instructions of each harness tightening procedure to the best of his/her ability. The trials were supervised to ensure proper adherence to the protocols. When the operator was finished making adjustments to a trial, he announced he was finished. The load cell reading was allowed to settle for approximately three second before the value was recorded by the researcher. The researcher unbuckled and loosened the harness until the output meter returned to zero. The position of the ATD was checked in between each trial but was not fully removed.

After each set of 10 repetitions of the same procedure, the operators completed a feedback survey. They were asked to rate the procedure's ease-of-use and their level of previous experience using the procedure.

Participants

A total of 7 sled room operators were recruited across 4 different sled testing facilities in the US. Inclusion criteria required that each participant was currently employed in a position where they routinely position ATDs into CRS and tighten the five-point harness. Operators completed background surveys to establish their length of employment in their position, their facility's typical procedure for harness tension verification, sex, and age.

Data Analysis

All statistical analyses were done using JMP Pro 13 (SAS Institute Inc., Cary, NC). Descriptive analyses were done for the harness tension produced by each procedure across the entire group. One-way analysis of variance (ANOVA) was used to evaluate whether procedure was significantly associated with harness tension. Once a significant association was found, Tukey's post-hoc tests were conducted to analyze the differences in tension magnitudes among procedures. Procedures which produced the highest and lowest tensions were identified. Two-tailed t-tests were used to examine differences between the two CRS models.

Next, ANOVA and Tukey's post-hoc tests were conducted to compare tension outcomes across operators within each procedure. Results were evaluated to identify whether different operators were able to produce statistically similar tensions relative to one another when the same procedure was used.

Lastly, the coefficients of variation (CV) were calculated to evaluate the repeatability of each operator against his/her own performance within each procedure. The CV is the ratio of the standard deviation to the mean and is typically expressed as a percentage. The CV allows for comparison of variation between groups while taking into consideration that the means are quite different from one another.

Results

Information about the seven sled room operators is shown in Table 1.

Distributions of the harness tension for all operators and both CRS models are shown in Figure 6.

ANOVA results show that procedure is significantly associated with harness tension considering all operators combined.

Tukey's post-hoc test was run to identify differences in harness tension magnitudes between the procedures using the aggregated data from all operators.

Tukey's post-hoc test shows that the two finger procedure produced the highest harness tension. The 3-prong gauge and

TABLE 1 Background and demographic information was collected for each of the seven sled room operators recruited for participation.

Operator	Facility	Typical Procedure	Experience	Sex	Age
1	B	Two finger	2 years	M	43
2	C	3-prong gauge	4 years	M	35
3	A	Two finger/3-prong gauge	0.5 years	M	26
4	B	Two finger	12 years	M	39
5	A	Two finger/3-prong gauge	3 years	M	35
6	C	3-prong gauge	1 week	F	56
7	D	3-prong gauge	2 years	F	37

FIGURE 6 Harness tension is displayed for all operators using each of the five tightening procedures on the standard box-and-whisker plot.

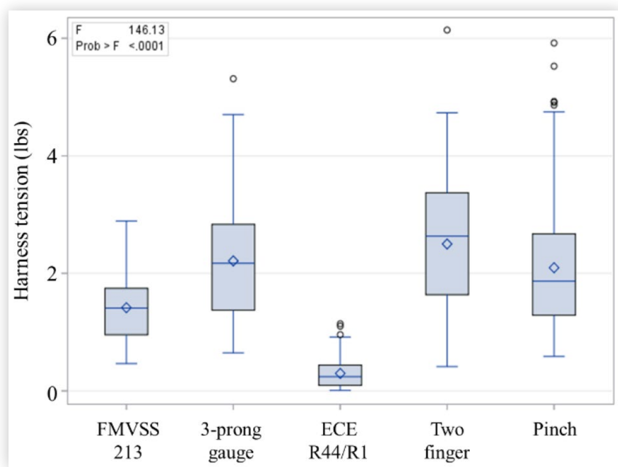


TABLE 2 ANOVA results showing significant association between procedure and harness tension.

Source	DF	R-Square	ANOVA SS	F Value	Pr > F
Procedure	4	0.456831	434.87657	146.13	<.0001

TABLE 3 Tukey's post-hoc test compares procedure means across all operators.

Procedure	Tukey Grouping	Mean (lbs)	N
Two finger	A	2.50	140
3-Prong gauge	B	2.21	140
Pinch	B	2.10	140
FMVSS 213	C	1.42	140
ECE R44/R129	D	0.30	140

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pinch procedure tensions were not significantly different from one another. The FMVSS 213 procedure produced the second-to-lowest tension, while the ECE R44/R129 procedure produced significantly lower tension than any other procedure.

Differences between the two CRS models were analyzed using two-tailed t-tests.

Significant differences exist between the two CRS models for the 3-prong gauge, ECE R44/R129, and two finger procedures. Neither CRS had consistently higher or lower tension values compared to the other. The combined results for both CRS are presented for the remainder of the analysis, because an ideal harness tightening procedure would have low variability and similar outcomes across all CRS types.

Next, differences in tension values between operators were investigated. A separate ANOVA was run for each procedure to test for significant differences among operators within each procedure. The condensed ANOVA results show that procedure is significantly associated with operator for each procedure (Table 5).

Tukey's post-hoc test was used to further evaluate differences in harness tension magnitudes among operators within each procedure. A procedure which is highly reproducible among operators would show all operators within the same Tukey grouping. A procedure with a larger number of Tukey groupings indicate that operators are producing results which are significantly different from one another despite following the same procedure.

The additional "Target" column in the 3-prong gauge section refers to the specific target that each operator selected within the 2-4 lb range suggested by the 3-prong gauge procedure text. The operators found that the 2-4 lb range was quite wide and all elected to select a more precise target within that range for their gauge readings during this procedure.

The range of the means in Table 6 shows widely different outcomes among operators for all five procedures. The Tukey groupings show that all five procedures had at least three distinct groupings of means when sorted by operator. Most procedures had at least one operator who was not grouped with any other operator, which indicates poor reproducibility. Some of the procedures show overlap among groupings, which might indicate slightly better reproducibility.

To evaluate the repeatability of each operator within each procedure, the coefficient of variation (CV) was calculated (Figure 7).

Most CVs range between 15% to 40% except for ECE R44/R129. The ECE R44/R129 procedure had the highest CVs for most operators. Because the mean tensions were so small for this procedure, small amounts of variation represent a large proportion of that mean. The CVs for the remaining four procedures are not vastly different from one another, indicating similar repeatability for these procedures.

TABLE 4 Two-tailed t-tests compare differences in harness tension between the two CRS models, by procedure.

Procedure	Apt 40RF	Alpha Elite 65	p-value
FMVSS 213	1.33	1.50	0.0787
3-Prong gauge	2.41	2.02	**0.0196**
ECE R44/R129	0.22	0.37	**0.0004**
Two finger	2.74	2.26	**0.0110**
Pinch	2.10	2.09	0.9273

TABLE 5 ANOVA results show significant association between operator and harness tension within each procedure.

	FMVSS 213	3-Prong Gauge	ECE R44	Two finger	Pinch
Source:	Operator	Operator	Operator	Operator	Operator
DF:	6	6	6	6	6
F Ratio:	15.797	37.754	36.303	70.804	45.42
Pr > F:	<.0001	<.0001	<.0001	<.0001	<.0001

TABLE 6 Tukey's post-hoc test compares operator means within each procedure. The sample sizes are n=20 for each row,

	Operator Number	Tukey Grouping				Mean (lbs)	Std Dev (lbs)	
FMVSS 213	6	A				1.89	0.54	
	3	A	B			1.79	0.44	
	7	A	B	C		1.52	0.54	
	2		B	C		1.45	0.46	
	4		B	C		1.37	0.32	
	1			C		1.17	0.49	
	5				D	0.71	0.16	Target
3-Prong Gauge	5	A				3.40	0.99	4.0
	2	A	B			2.82	0.51	4.0
	3		B	C		2.68	0.58	4.0
	1			C		2.16	0.44	3.0
	6			C		2.12	0.88	4.0
	7				D	1.37	0.27	3.0
	4				D	0.94	0.23	2.5
ECE R44/R129	3	A				0.71	0.23	
	2		B			0.39	0.22	
	5		B			0.37	0.17	
	1			C		0.20	0.10	
	6			C		0.18	0.15	
	7			C		0.16	0.12	
	4			C		0.07	0.04	
Two Finger	3	A				3.56	0.88	
	1	A				3.37	0.41	
	5	A				3.14	0.54	
	2	A				3.13	0.62	
	6		B			2.05	0.44	
	7			C		1.16	0.44	
	4			C		1.08	0.45	
Pinch	5	A				3.80	1.13	
	3		B			2.63	0.46	
	2		B			2.18	0.63	
	1		B	C		2.07	0.55	
	6			C	D	1.58	0.45	
	7				D	1.24	0.31	
	4				D	1.17	0.34	

FIGURE 7 Coefficients of variation (CV) are sorted by operator and procedure.

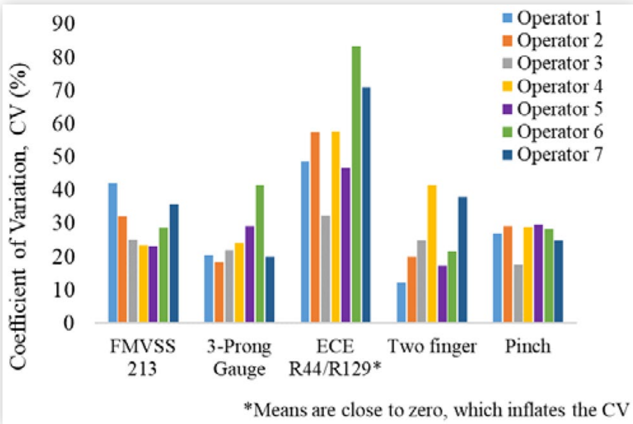
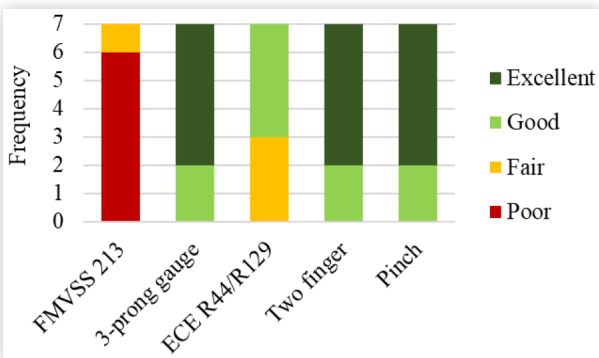


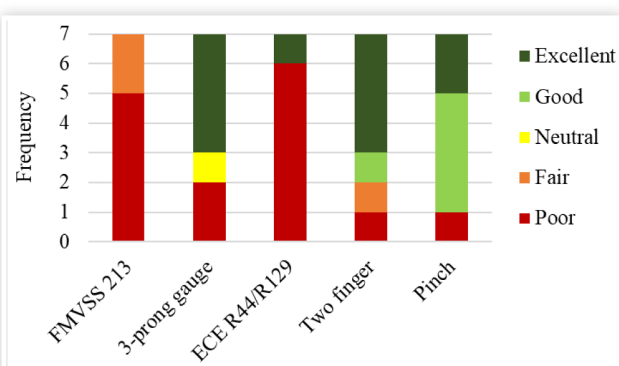
FIGURE 8 Operators ranked each procedure for ease-of-use.



The ease-of-use rankings of each procedure is shown in Figure 8. Operators found the FMVSS 213 procedure quite difficult to perform. Operators preferred the 3-prong gauge, two finger, and pinch procedures.

Each operator's self-identified level of previous experience using each procedure is shown in Figure 9. Most operators had very little experience with the FMVSS 213 or ECE R44/R129 procedures, while more were familiar with the 3-prong gauge, two finger, and pinch procedures. One operator did not have previous experience with any of the procedures because she had only been in her position for one week prior to participation in this study.

FIGURE 9 Operators ranked their level of previous experience with each procedure.



Discussion

The five harness tightening procedures produced a range of tensions in the experimental setup (Figure 6). The ECE R44/R129 procedure produced very low tensions. The slack in the harness was visible and several operators speculated that harness tensions this low might produce poor injury metric outcomes in dynamic sled tests. The remaining four procedures resulted in tensions that were more visibly acceptable to the operators.

Some differences in tension outcomes were found between the two CRS models. This indicates that differences in CRS design and geometry might affect harness tension outcomes even when the same procedure is performed on each.

Differences in tension between operators were evident for all five tightening procedures (Table 6), indicating that the reproducibility of all the procedures is low. The reproducibility of the 3-prong gauge procedure might be improved by offering a more specific target for the reading on the gauge. The operators found that the 2-4 lb range in the instructions was quite wide. All operators elected to select a more precise target within that range for their gauge readings. The mean tensions for each operator roughly correlate with the targets that each operator chose. Operators 5, 2, and 3 chose the upper end of the target range (4 lbs) and produced the highest mean tensions of the group for this procedure. The operator who chose the smallest target (Operator 4; 2.5 lbs) produced the smallest tensions. In fact, this pattern among operator means can be observed across most of the procedures: Operators 5, 2, and 3 also produced tension means toward the higher end of the spectrum using the ECE R44/R129, two finger, and pinch procedures. Operators 7 and 4, who chose lower target values during the 3-prong procedure, were consistent in producing the lowest tensions across many of the other procedures. These patterns suggest that operators tend to produce tensions which align with their typical practice even when following a variety procedures. Interestingly, these patterns among operators do not hold true for the FMVSS 213 procedure. This result could be attributed to the operators' lack of previous experience with this procedure (Figure 9) and their reported difficulty in performing it according to the instructions (Figure 8). This outcome could also be a result of the FMVSS 213 procedure using an objective measuring tool, while the two finger and pinch procedures do not. Having a physical tool or gauge might help guide operators who may have preconceived ideas of how tight the harness should feel.

The five harness tightening procedures are not necessarily intended to produce the same harness tension. Without a "gold standard" tension target, we cannot perform a true gage repeatability and reproducibility (R&R) analysis. However, we have examined the differences in outcomes between operators and differences between trials for the same operator. These data indicate which procedures are robust against operators' various applications of the given guidelines. Further study is needed to determine what tension target is desirable and whether any particular tightening procedure achieves this target or can be modified to do so.

The data presented here encompass the range of tensions produced by different operators in different facilities. It is currently unknown whether crash outcomes are sensitive to these ranges of harness tension. Most existing literature investigates injury metric outcomes due to large amounts of slack [1, 2], not the smaller ranges presented here. However, these data might be used to establish boundary conditions for harness tension in future analyses of dynamic crash outcomes related to this variable.

The methodology of this study has revealed a few indirect observations. The high variation in the load cell tension readings could be attributed to the friction within the harness system. The harness webbing routes around the hips, torso, shoulders, and shell of the CRS. All of these contact points might result in varying levels of tension in different sections of the webbing. The load cell reading appeared to be sensitive to the operators pulling the harness in different directions. For example, pushing the chest clip upward on the ATD's torso caused the load cell reading to increase. This is because the upward motion of the chest clip removed the slack from the lower torso/hip region, which is where the load cell was incorporated. Similarly, adjusting the chest clip downward would usually cause a decrease in the load cell reading. In this case, the harness slack is being pulled out of the shoulder region and introduced into the lower torso/hip region.

This observation suggests that the harness does not function as a continuous, homogeneous loop of webbing. Areas of tautness and slack can exist at different locations within the harness due to friction throughout the system. The load cell was sensitive to these differences and its final reading appeared to depend on the direction of the operator's "final pull" on the harness. Unfortunately, these "final pull" adjustments were not controlled for during this study. Some operators were fairly consistent in their order and direction of adjustments while others were more sporadic. Sometimes the harness needed to be minutely tightened and/or loosened several times until the operator felt the outcome met the procedure guidelines.

The direction of the final pull might also affect whether the teeth of the front adjustor lock are engaged with the harness webbing. Pulling the front adjustor strap rotates the teeth on the lock such that they are not engaged and allows the strap to slide easily through the adjustor to tighten the harness. However, pulling sharply upward on the torso region of the harness causes the teeth to rotate into the adjustor strap and lock the harness into place. This motion simulates the locking of the mechanism when the harness is loaded during a crash. Sometimes operators pulled the harness and pre-engaged the teeth, while others did not. Thus, sometimes the spool-out slack created during this process was accounted for, while other times it was not.

It is unclear whether the location and direction of the final pull are significant factors in harness tension measurements because they were not tracked in this study. However, future studies should consider these observations and ensure that operators are consistent in the order and direction of their final harness adjustments.

The tension values read by the load cell in the webbing did not directly match to the readings on the 3-prong gauge during that procedure (Table 6). The tensions were being measured at different locations on the harness. This discrepancy is further evidence of high amounts of friction within the harness system which prevent it from behaving as a continuous, homogeneous system. Measuring techniques which consider more than one section of the harness webbing may be warranted in future studies.

Additional limitations of this study include the small sample size of seven operators and two CRS models. This study was not controlled according to which procedure(s) the operators were familiar with. None of the recruited operators routinely used the FMVSS 213 or ECE R44/R129 procedures at their facilities. At the time of data collection, the authors were not aware of any facilities in the US which routinely employed these procedures. The CRS were installed on different versions of the FMVSS 213 bench, depending on availability at the different test sites. Effects of the test bench version cannot be isolated from operator biases since each operator was tested on only one test bench. All versions of the bench had similar seat pan angles and seat back angles (within 3 degrees of one another). The main difference between benches was the stiffness of the foams, which was assumed irrelevant for this testing protocol. The 3-year-old Hybrid III offered a reasonable amount of space for the operators to adjust the harness according to each procedures' instructions. A smaller ATD might pose additional challenges due to reduced accessibility of the harness. CRS models which include harness covers or additional padding might also complicate harness tightening procedures.

Summary/Conclusions

The five harness tightening procedures produced different magnitudes of tension. The ECE R44/R129 procedure produced low tensions across all operators, while the two finger procedure produced the highest tensions.

Significant differences in tension means existed across operators even when the same procedures were followed, which implies poor reproducibility of the procedures as written. The CVs of the datasets ranged between 15% to 40% for most procedures, which is higher than expected. This result implies poor repeatability within operators.

Future studies should consider the high amount of friction in the harness system as the webbing routes around the hips, torso, shoulders, and CRS shell. The friction might cause different tension readings depending on the location of measurement and the direction of the operator's last adjustment on the webbing.

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Appendix A

The routing of the harness webbing in relation to the load cell is shown here. When the front adjuster strap is pulled (front), the splitter plate is pulled downward (back). This creates upward tension in the shoulder and hip areas (front), which creates outward lateral tension on the load cell (back).

Appendix B

For Procedure B, the 3-prong gauge should be positioned on the webbing halfway between the chest clip and the buckle, and should be slid on from the outside (lateral) facing inward (medially),

Appendix C

For Procedure C (ECE R44/R129), the spacer was positioned behind the ATD as shown. The hand-held digital tension gauge was used to pull the front adjuster strap at a 45° angle to a tension of 250 N.

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