Methodologies for Blunt Trauma Assessment in Military Helmets

J. Hopping[1], C. Bass[2], J. Shridharani[2], C. Perritt[1], N. Haynes[1], and K. Masters[1]

[1]*Technical Management Division (TMD), Project Manager Soldier Protection and Individual Equipment (PM SPIE), 15395 John Marshall Hwy Haymarket, VA 20169*
jakob.a.hopping@us.army.mil
[2]*Duke University: Department of Biomedical Engineering, 136 Hudson Hall, Durham, NC 27708*

Abstract. Since World War II, U.S. military combat helmets have provided various degrees of protection against ballistic threats, including fragments and bullets. Only recently, however, have combat helmets been specified to provide blunt impact protection. This study assesses the current generation of combat helmets and four commercial off the shelf (COTS) pad suspension systems (denoted A, B, C, and D) for blunt impact protection against realistic blunt impact threats including falls, parachute drops, and motor vehicle crashes using a drop test methodology based upon the Advanced Combat Helmet (ACH) Purchase Description (CO/PD-05-04) and the U.S. Department of Transportation (DOT) Laboratory Test Procedure for Motorcycle Helmets (TP-218-06). Three variant headforms (DOT, NOCSAE, and ISO) and three independent testing laboratories were used to examine 549 helmet samples with a total of 7,686 impacts. A single ballistic shell manufacturer was used to reduce potential variability. All five fielded helmet sizes (S, M, L, XL, and XXL) were included in the study, and impacts were conducted at three temperature conditions (263±5°K, 295±4°K, and 327±5°K) as well as at three impact velocities (3.0±0.1m/s, 4.3±0.1m/s, and 5.3±0.2m/s). For the DOT headform tests, hot temperature conditions showed substantially greater peak acceleration than the cold or ambient conditions (~60g across all tests). Peak acceleration values from the first DOT headform impact averaged 30g less than those measured during a repeat impact. On average, the peak impact accelerations measured in the NOCSAE headform were 48g less than those measured in the DOT headform and 74g less than those measured in the ISO headform, across all velocities. As the impact velocities increased, this effect became more pronounced. Careful consideration should be given to advantages and disadvantages of each test headform for future testing. Detailed headform anthropometry may be an issue for assessment of higher performance helmets and should be further evaluated.

1. INTRODUCTION

Protective equipment should be designed to address the full spectrum of realistic threats. Since World War II, U.S. military combat helmets have provided various degrees of protection against ballistic threats, including fragments and bullets. Only recently, however, have combat helmets been specified to provide blunt impact protection [1]. This study assesses the current generation of combat helmets for protection against realistic blunt impact threats and provides the basis for further developing test methodologies to assess these threats.

There are many threats to the Soldier's head, and blunt impacts are a significantly large fraction of the total spectrum of these threats. The risk of injury due to blunt impact in operational conditions is high for many reasons. First, military operations occur during all times of day under diverse environmental and lighting conditions. For night operations and other operations on foot, falls or collision impacts are a common risk. Typical drop heights for falls range from 1-2m with impact velocities from 4-6m/s. Parachute drop velocities range from 5-6m/s [2], and impact velocities resulting from motor vehicle crashes may range from 3-15m/s. In addition, vehicle impacts during military operations are a frequent source of morbidity and mortality for military personnel [3].

Realistic protection requirements for the military may be greater than those developed for civilian applications. In particular, some civilian blunt impact injury threshold requirements include injury assessment values that indicate a potential for the loss of victim consciousness; however, maintaining consciousness is arguably more critical in an operational military environment. Consciousness is essential to provide an injured Soldier a greater degree of "fightability" (i.e. an ability to engage enemy threats, self extract, and communicate). Although military blunt impact standards often mirror those developed for civilian applications, military blunt impact injury threshold requirements must be tailored to provide the unique level of protection that is needed in a military context.

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14. ABSTRACT

Since World War II, U.S. military combat helmets have provided various degrees of protection against ballistic threats, including fragments and bullets. Only recently, however, have combat helmets been specified to provide blunt impact protection. This study assesses the current generation of combat helmets and four commercial off the shelf (COTS) pad suspension systems (denoted A, B, C, and D) for blunt impact protection against realistic blunt impact threats including falls, parachute drops, and motor vehicle crashes using a drop test methodology based upon the Advanced Combat Helmet (ACH) Purchase Description (CO/PD-05-04) and the U.S. Department of Transportation (DOT) Laboratory Test Procedure for Motorcycle Helmets (TP-218-06). Three variant headforms (DOT, NOCSAE, and ISO) and three independent testing laboratories were used to examine 549 helmet samples with a total of 7,686 impacts. A single ballistic shell manufacturer was used to reduce potential variability. All five fielded helmet sizes (S, M, L, XL, and XXL) were included in the study, and impacts were conducted at three temperature conditions (263±5°K, 295±4°K, and 327±5°K) as well as at three impact velocities (3.0±0.1m/s, 4.3±0.1m/s, and 5.3±0.2m/s). For the DOT headform tests, hot temperature conditions showed substantially greater peak acceleration than the cold or ambient conditions (~60g across all tests). Peak acceleration values from the first DOT headform impact averaged 30g less than those measured during a repeat impact. On average, the peak impact accelerations measured in the NOCSAE headform were 48g less than those measured in the DOT headform and 74g less than those measured in the ISO headform, across all velocities. As the impact velocities increased, this effect became more pronounced. Careful consideration should be given to advantages and disadvantages of each test headform for future testing. Detailed headform anthropometry may be an issue for assessment of higher performance helmets and should be further evaluated.

15. SUBJECT TERMS

Combat Helmet; Advanced Combat Helmet; ACH; Helmet Test Method; Blunt Impact Protection; TP-218-06; Laboratory Test Procedure for Motorcycle Helmets; NOCSAE Headform; DOT Headform; ISO Headform; Headform Anthropometry; Pad Suspension System; Head Injury Assessment; Monorail Drop Tower

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1.1 Head Injury Assessment

Although head and skull injury assessment studies have been performed for sixty years [4], most major advances in head protection have occurred during the last thirty. During this time, the increased use of helmets in athletics and the improvements in helmet design have dramatically reduced both the frequency and severity of head and neck injuries. The development of standardized test methodologies for assessing blunt impact performance is credited as a critical driver for improvements in helmet design [5]. AGARD AR-330 lists a representative sample of twenty-nine international blunt impact test standards, and each of these standards has some form of impact acceleration limiting criterion [6]. Two-thirds (19) of these standards are based on acceleration or force peaks alone, and one-third (10) are based on acceleration/duration levels. The desired acceleration threshold specified by these standards ranges from 150g to 400g, but recent studies of football impacts suggests that a threshold level of approximately 80g should be used to provide protection against changes in mentation [7].

1.2.1 Advanced Combat Helmet (ACH) Blunt Impact Test Methodology and Standard

The current U.S. Army blunt impact test methodology [1] is based on the U.S. Department of Transportation (DOT) Laboratory Test Procedure for Motorcycle Helmets (TP-218-06) [8]. TP-218-06 specifies a guided monorail drop and provides requirements for how helmets should be mounted, the headform size that should be used, the location of the impact, the drop height, the drop surface, the weight of the supporting assembly, and other factors that help to increase the reproducibility of the test. Drop velocities include 6.0 m/s with a flat anvil and 5.2m/s with a hemispherical anvil. The monorail restricts movement to control the impact location, and acceleration is measured using a uniaxial accelerometer. TP-218-06 allows a maximum headform acceleration of 400g with duration-related maxima of 200g for more than 2ms and 150g for more than 4ms. The DOT headform used in this methodology is an anthropometrically simplified, low resonance, rigid cast headform [9]. It is roughly hemispherical in shape and its detailed geometry is intended to model the size, shape, and weight of adult heads in the U.S. [8].

Although the current U.S. Army blunt impact test methodology is based upon TP-218-06, several significant deviations from the base method are taken. The peak acceleration for a DOT headform fitted in the ACH helmet with padding is limited to less than 150g given an impact velocity of 3.0 m/s on a hemispherical impactor at ambient (295 ± 4^{o}K), cold (263 ± 5^{o}K), and hot (327 ± 5^{o}K) temperatures. The 150g requirement does not control for duration of exposure. Seven impact locations (crown, left side, right side, front, back, left nape, and right nape) are specified, and the test methodology requires a repeated impact within 90 ±30 seconds of the first impact at each impact point.

1.2.2 Additional Blunt Impact Test Methodologies and Standards

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) was formed in 1969 to facilitate the mitigation of football injuries and fatalities. NOCSAE adopted the Wayne State headform, and this headform is designed to represent human geometric, inertial, and frequency responses [10]. The NOCSAE headform has a glycerin-filled brain cavity, and it may have enhanced dynamic and anthropometric biofidelity as compared with metallic headforms. The NOCSAE blunt impact test methodology uses a 12.7mm thick Modular Elastomer Pad (MEP) flat impact surface with a wire guided drop, and test velocities include 4.2m/s, 4.9m/s, and 5.5m/s [11]. Accelerations are assessed using a triaxial accelerometer, and injury risk is assessed with the severity index (SI). NOCSAE passing criteria for football helmets is an SI limit of 1200.

The American Society for Testing and Materials (ASTM) specifies two types of rail-guided tests to determine the blunt impact resistance and retention system performances of equestrian helmets in ASTM 1163 [12]. ASTM 1446 specifies the method for these tests [13], and the ASTM uses the International Standards Organization (ISO) headform for blunt impact testing. The ISO headform is similar to the DOT headform in that it is an anthropometrically simplified, low resonance, rigid cast headform. The headform is designed to be similar in shape to a human skull, but the headform does not extend much inferior to the Frankfort plane. The ASTM standard includes impact velocities of 6.0 ±0.2m/s and 5.0 ±0.2fps onto both a MEP and an anvil with a circular base leading to an edge [13]. Accelerations are measured with a uniaxial accelerometer and passing criteria is accelerations less than 300g.

Additional test methodologies include a multiple pendulum device that allows a single rotational degree of freedom [14]. The benefit in using this setup comes in that the nonrigid impacting surface does not influence the stress distribution as seen in the conventional rigid impacting surfaces used in standard drop tests. Verschueren et alia claim a ten percent uncertainty in the energy absorbed in the skull with this method. Other available blunt impact headforms include the Hybrid III [15], Thor [16], and FOCUS headforms [17], all used in automobile as well as military test standards and research. These headforms allow additional instrumentation including maxillofacial contact instrumentation.

2. METHODOLOGY

This study assesses the current generation of combat helmets and four commercial off the shelf (COTS) pad suspension systems (denoted A, B, C, and D) for blunt impact protection against realistic blunt impact threats including falls, parachute drops, and motor vehicle crashes using a variation of the ACH blunt impact test methodology with DOT, NOCSAE, and ISO headforms. Testing was conducted at three accredited commercial laboratories on all five current helmet sizes (S, M, L, XL, and XXL). However, a single ballistic shell manufacturer was used to reduce potential variability. A total of 549 helmet samples were examined, and samples were tested at three temperatures (263±5°K, 295±4°K, and 327±5°K) and at three impact velocities (3.0±0.1m/s, 4.3±0.1m/s, and 5.3±0.2m/s). Each helmet sample was impacted twice at seven locations (front, right side, left side, crown, left nape, right nape and rear) with a monorail impact device as shown in Figure 1. In total, over 7,686 impacts were conducted, and each test condition is portrayed in Tables 1 and 2.

This study was performed in four phases: 1) a comparison of laboratory repeatability and consistency, 2) impact testing with the DOT headform, 3) impact testing with the NOCSAE headform, and 4) impact testing with the ISO headform. The ACH blunt impact methodology specifies that repeat impacts must occur 90 ±30 seconds after the first. For this data set, each repeat impact was conducted as close to 60 seconds after the first as permitted by the test apparatus. The DOT headform size associated with each helmet size is shown with the associated test matrix in Table 1. Likewise, the NOCSAE headform size associated with each helmet size and the ISO headform size associated with each helmet size is shown in Table 2 with the associated test matrix for each headform.

Figure 1. Monorail drop tower (left), DOT headform (center left), and ACH blunt impact locations (+) on a NOCSAE headform (center right and right)

Table 1. Test matrix for DOT headform[a]

Temperature	**Hot**			**Ambient**			**Cold**		
Impact Velocity (m/s)	**3.0**	**4.3**	**5.3**	**3.0**	**4.3**	**5.3**	**3.0**	**4.3**	**5.3**
Helmet Size S (DOT size B)	168	168	168	168	168	168	168	168	168
Helmet Size M (DOT size C)	168	168	168	168	168	168	168	168	168
Helmet Size L (DOT size C)	168	168	168	168	168	168	168	168	168
Helmet Size XL (DOT size D)	168	168	168	168	168	168	168	168	168
Helmet Size XXL (DOT size D)	42	42	42	42	42	42	42	42	42
Total	**714**	**714**	**714**	**714**	**714**	**714**	**714**	**714**	**714**

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[a] Type A through D pads were used for all but size XXL helmets. Type D pads were the only pads available for the size XXL helmet.

Table 2. Test matrix for NOCSAE and ISO headforms[b]

NOCSAE Headform					ISO Headform			
Helmet Size	**Headform Size**	**Impact Velocity (m/s)**			**Headform Size**	**Impact Velocity (m/s)**		
		3.0	**4.3**	**5.3**		**3.0**	**4.3**	**5.3**
S	S	42	42	42	E	42	42	42
M	S	42	42	42	J	42	42	42
L	M	42	42	42	J	42	42	42
XL	M	42	42	42	M	42	42	42
XXL	L	42	42	42	O	42	42	42
Total		**210**	**210**	**210**		**210**	**210**	**210**

2.1 Statistical Methodology – General Linear Model

Statistical significance and trends are evaluated in this study using a General Linear Model (GLM). The GLM is a generalized method to analyze the variance in test datasets, and this technique allows the assessment of independent variation of both categorical and continuous variables. The GLM also supports the examination or identification of unbalanced experimental designs as well as of the general interactions between variables. Table 3 lists the variables that are examined with a GLM in this study. The GLM used is of the form:

$$\text{Acceleration} = \text{Constant} + \beta_1 \cdot \text{Variable}_1 + \beta_2 \cdot \text{Variable}_2 + \ldots + \text{Higher Order Terms.} \qquad (1)$$

Table 3. Categorical, Continuous and Response Variables for General Linear Model

Categorical Variables	
Padding Type	Current (A, B, C, D)
Temperature	Cold (263^{0}K), Ambient (295^{0}K), Hot (327^{0}K)
Helmet Size	S, M, L, XL, XXL
Impact Location	Crown, Front, Back, Right Nape, Left Nape, Left Lateral, Right Lateral
Drop Number	Two drops per impact site
Continuous Variable	
Drop Velocity	3.0m/s, 4.3m/s, 5.3m/s
Response Variable	
Acceleration	Peak/duration and time histories

3. RESULTS

3.1 Preliminary Interlab Comparisons

In order to expedite testing and result analysis, parallel testing was conducted at three different laboratories. There were potential variations in test apparatus setup at these three labs, so a subset of the testing was performed to assess the repeatability and consistency of test results between labs. The lab repeatability evaluation was conducted under ambient temperature conditions (295 ±4°K) with a size large helmet shell fitted to a DOT size "C" headform for 42 test conditions with 2 repeated impacts at 7 impact sites. All repeatability tests were conducted with the D pad suspension system at a blunt impact velocity of 4.3±0.1m/s. The peak impact results of these tests are shown in Figure 2.

The GLM for the preliminary interlab comparison shows that peak headform acceleration due to blunt impact is sensitive to small changes in impact velocity. The average impact velocity for the test apparatus at Lab 1 (4.30m/s) and Lab 3 (4.33m/s) are statistically significantly different from that for Lab 2 (4.34m/s). Figure 2 shows the variation in average impact velocity between the three testing facilities. Although this velocity variation is within the allowed margin of error (±0.2m/s), it caused statistically significant differences in peak headform acceleration results between the three laboratories for both the first and second impacts at each of the seven impact locations. When a velocity interaction term is included within the GLM, the difference in peak headform acceleration between labs is no longer statistically

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[b] All impacts at ambient 72±4^{o}F temperatures and with type D pad suspension systems

significant. To properly assess statistical differences in measured acceleration, either a velocity interaction term should be included within the GLM or the allowable velocity deviation should be restricted to a smaller range. GLMs for all remaining tests within this study include a velocity term to account for this issue.

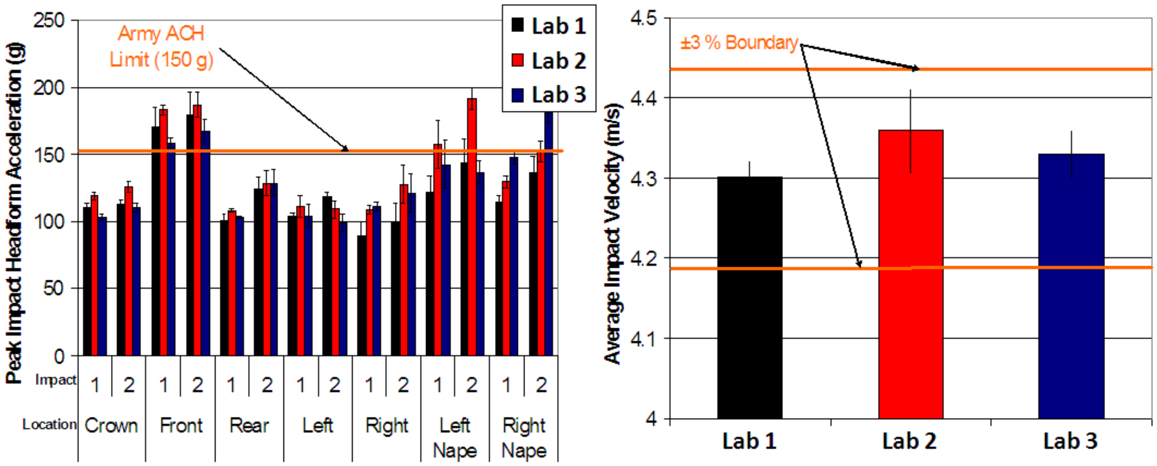

Figure 2. Comparison test results (left), and mean impact velocity for the interlab comparison by lab (right)

3.2 DOT Headform Test Results

The DOT headform is the headform used for the ACH blunt impact test methodology. This methodology requires pad suspension systems to attenuate blunt impacts to 150g or less. Thirty-six DOT headform test conditions were tested for each pad suspension type (A, B, C, and D).[c] These test conditions include 4 helmet sizes (S, M, L, and XL), 3 impact velocities (3.0±0.1m/s, 4.3±0.1m/s, and 5.3±0.2m/s), and 3 temperature conditions (263±5°K, 295±4°K, and 327±5°K). Each of these test conditions were tested using 3 sample helmets with 14 impacts each. Table 4 lists the number of tested conditions that met the ACH standard of less than 150g for every impact, the number that met the standard on average, and the number that averaged 150g or more. Pad type D met the 150g ACH requirement for a total of 12 test conditions, mostly 3.0 m/s velocity conditions, and pad type C met the 150g test requirement for a total of 10 test conditions. Pad type A had 9 test conditions that met the ACH requirement, and pad type B had 8.

Table 4. Number of conditions that met the ACH standard by pad type

Pad Type	All Peak Acc. < 150 g	Mean Peak Acc. < 150 g	Mean Peak Acc. ≥ 150 g
A	9	3	24
B	8	11	17
C	10	4	22
D	12	10	14

GLM results in Figure 3 show that velocity, temperature, and impact number had a strong effect on acceleration value for DOT headform tests. All coefficients shown in Figure 3 are statistically significant (α=0.05), and the R^2 of the overall model is 0.56. The hot condition showed substantially greater peak acceleration than the cold or ambient conditions (~60g across all tests). Peak acceleration values from the first impact averaged approximately 30g less than those measured during the second impact. Further GLM results show that helmet size does not have a large effect compared with velocity or temperature. Average peak acceleration differences due to helmet size are less than 15g. However, blunt impact location has a large effect on peak acceleration. The crown, left side, and right side impact locations had the lowest acceleration values. Subsequently, these impact locations also have the lowest GLM coefficients. The impact location coefficients exhibit bilateral symmetry. Those for left and right side impacts are within one standard deviation of each other, and those for the left and right nape impacts are within two standard deviations of each other. The back, left nape, and right nape locations generally produced the greatest

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[c] XXL helmet results were excluded for comparability because pad type D was the only available pad type for the XXL helmet.

acceleration values. This may be the result of local headform geometry and limited standoff in those locations. The left and right nape acceleration values were approximately 80g greater than those observed during the crown impacts.

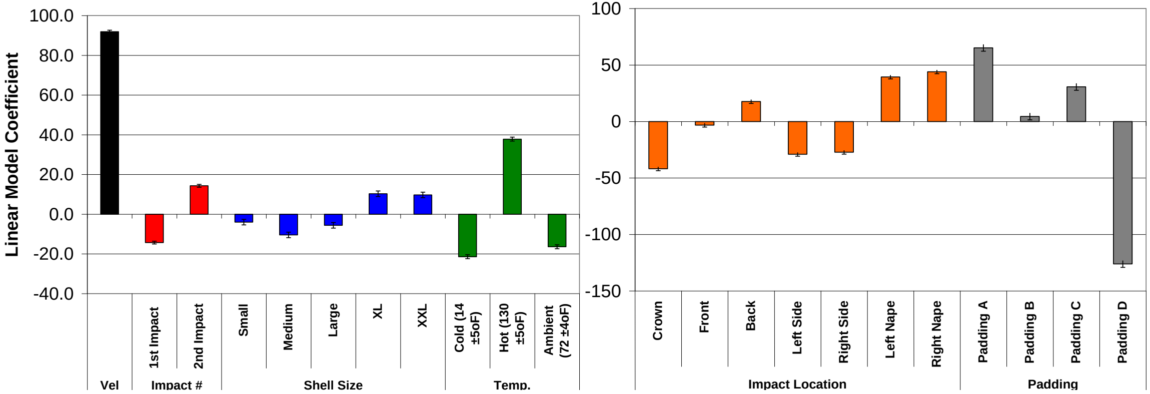

Figure 3. GLM results for all DOT headform test conditions

3.3 NOCSAE and ISO Headform Testing

The results from the DOT headform were compared with the NOCSAE and ISO results from the same test conditions. The compared test results include ambient (295±4°K) condition tests at 3.0m/s, 4.3m/s, and 5.3m/s. All five helmet shell sizes were compared, including the XXL, with the type D pad suspension system. Figure 4 shows the comparison of the average headform accelerations for each impact site by headform type at impact velocities of 3.0 ±0.1m/s and 5.3±0.2m/s. The peak accelerations observed in the NOCSAE headform are significantly lower than those in the DOT and ISO headforms. On average, the peak impact accelerations measured in the NOCSAE headform were 48g less than those measured in the DOT headform and 74g less than those measured in the ISO headform, across all velocities. As the impact velocities increased, this effect became more pronounced. The anthropometric biofidelity in the nape region for the NOCSAE headform or lack thereof for the DOT or ISO headforms may be a contributing factor to the large difference in average acceleration between these headforms. Table 5 shows the mean peak headform acceleration by headform type for both crown and combined nape impacts at velocities of 3.0m/s and 5.3m/s.

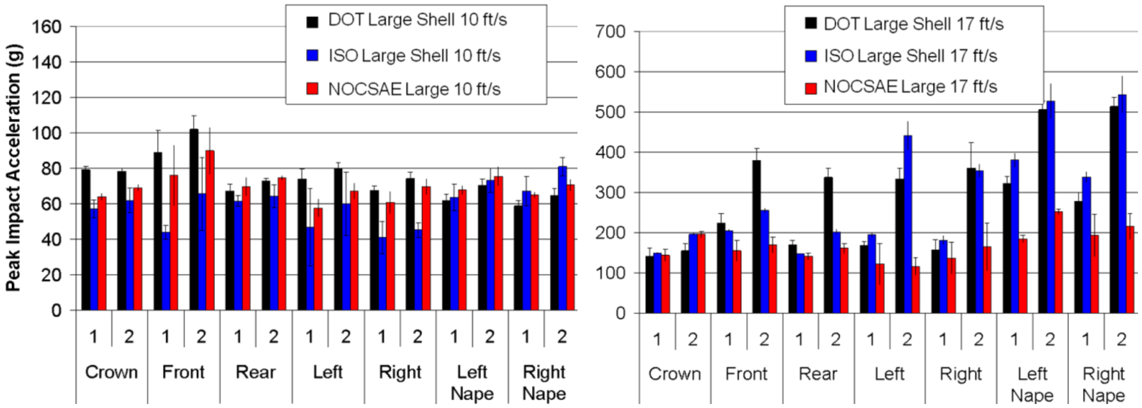

Figure 4. Ambient temperature (295 ±4°K) peak headform accelerations by impact location and headform type for impact velocities of 3.0±0.1m/s (left) and 5.3±0.2 m/s (right)

Table 5. Mean peak acceleration for the crown and nape impact locations by headform type

Impact Location	Impact Velocity	DOT Headform	NOCSAE Headform	ISO Headform
Crown	3.0m/s	77	64	68
	5.3m/s	213	184	215
Left & Right Nape	3.0m/s	76	63	71
	5.3m/s	389	207	495

4. DISCUSSION AND CONCLUSIONS

The current ACH blunt impact velocity specification of 3.0m/s is equivalent to a fall from a height of approximately 0.5m. An assessment of potential operational threats indicates head impact velocities of 4.3m/s (equivalent to a half-height fall from 1.0m) and 5.3m/s (equivalent to a three-quarter height fall from 1.5m) may be a more realistic blunt impact standard. Adopting a more realistic blunt threat likely will pay off with increased operational readiness and with a reduction in head impact casualties. The current limit to helmet standoff may also restrict further pad suspension system performance. Typical commercial blunt protective helmets have a 25 to 44mm standoff with typically stiffer initial deformation. Increasing the ACH standoff to this range may improve blunt impact protection by allowing the use of additional padding. Although the current requirement does not represent a realistic threat, current pad suspension systems testing indicates that passing a 4.3m/s standard will be difficult with the current standoff, geometry, and other performance requirements.

4.1 Theoretical Standoff Limitations to Performance

The mean of the 3.0m/s peak acceleration results presented here is 86.8 ±22.0g. Assuming a Gaussian (normal) distribution of peak accelerations, the 150g performance limit is approximately 3σ from the mean. Therefore, approximately 1 out of every 500 impacts will result in a failure due to pad sample and testing variability. At this level of variability, an average of 90g is the approximate pad performance necessary to avoid a high risk of failing the 150g inspection criteria. Pad suspension systems designed to meet the 150g criteria at higher impact velocities must either attain a headform acceleration average of 90g or reduce variability in test results. Variability could be decreased by: improving headform anthropometry, limiting the target temperature range, or eliminating repeat impact requirements. *Each of these tradeoffs should be assessed in the context of operational threat assessments and available operational injury epidemiology.*

The current design standoff from the ACH shell to the head is 19 to 25mm, and the pad suspension system that fills this gap is significantly deformed during proper helmet use. If pad suspension systems must average a uniform deceleration of 90g to meet impact attenuation specifications, then a deformation of approximately 5mm or 20% to 25% of the available standoff is necessary to attenuate 3.0m/s impacts. This analysis does not account for realistic acceleration ramp rates, and many closed cell foams may not be capable of deformation beyond 40% of their original length without substantial increases in acceleration. If we assume that the current pad suspension systems are representative of the level of impact attenuation that can be achieved per thickness of pad, then we may make ratiometric estimates of the pad thickness required to achieve successful impact attenuation at various velocities, as shown in Figure 5.

Using the standard deviation for the dataset presented here, a 3.0m/s impact would require 19mm of standoff, while a 5.3m/s impact would require 58mm. As shown in Figure 5, the elimination of repeat impacts does not decrease this value substantially. However, decreasing the temperature range required will decrease the variance significantly and thereby reduce required standoffs. For example, if temperature requirements were limited to ambient only conditions with the current dataset, the 5.3m/s impact standoff requirement is reduced to 46mm. For reference, a standoff of approximately 44mm is similar to that used in current bicycle helmets.

4.2 Potential Test Methodology Modifications

Acceleration results were found to depend strongly on impact location and environmental conditions. In this study, the back, left nape, and right nape locations generally produced the greatest acceleration values. This may be the result of both local headform geometry and limited standoff in those locations. The linear model coefficients of the left and right nape acceleration values were approximately 80g greater than those observed during the crown impacts for this dataset. From the test results and comparison of the assessed headforms, especially the DOT headform [17], it is apparent that the headforms used are not especially anthropomorphic in the nape region. Therefore, it is possible that the actual helmet performance is greater in this region than that measured on the DOT headform. Redesigning the headform for improved anthropometry in the nape region could increase the biofidelity of helmet blunt impact assessments.

Tested pad suspension systems demonstrated significant performance sensitivity to temperature. As performance criteria increases, the impact of temperature variation on pad performance may also increase. Because of this strong dependence on temperature, future test methodologies should include realistic operational temperature ranges to prevent injuries in common temperature environments while avoiding unnecessary constraints on helmet blunt impact design with unrealistic temperature requirements.

In this study, there was limited account made for the retention system. Neither DOT nor ISO headforms have a chin. For this test series a ‘chin’ was manufactured for each test lab from stiff foam as shown in Figure 5. In future tests, to limit variation, a chin should be defined and a retention system tension should be specified to provide a complete specification of test conditions. Owing to the potential effect of initial deformation on impact test results, there also may be value in identifying the effect of tension on the impact results, especially for the peripheral impact locations.

Because there is a great degree of variation in blunt impact attenuation by impact location, the impact locations used in this study are well constrained. To assess production lots, however, it is desirable to include some variance to prevent point design by location. It may be desirable to augment the current seven impact locations with an additional eighth free impact point to assess any location on the helmet.

Impact number and shell size were found to have a moderate effect on acceleration peaks. The COTS pad suspensions are viscoelastic. The increase in peak acceleration values from the first to the second impact seen in this study could be due to insufficient viscoelastic pad recovery, material damage in the pads from the first impact, or material damage in the helmets from the first impact. The predominant viscoelastic time constant measured during material characteristic testing for one pad variant is approximately 45 seconds [18]. Repeat impacts during this study were 60 seconds apart, and the pad viscoelastic material cannot fully recover in such a short time interval. Pad suspension systems require on the order of minutes to fully recover from the first impact. Therefore, in order to reduce test variability, consideration should be given to reducing the allowed degree of variation in repeat impact time interval (currently ±30 seconds) and to increasing the overall time interval (currently 90 seconds). Alternatively, the multiple impact requirement can be further evaluated for testing benefit versus variability cost.

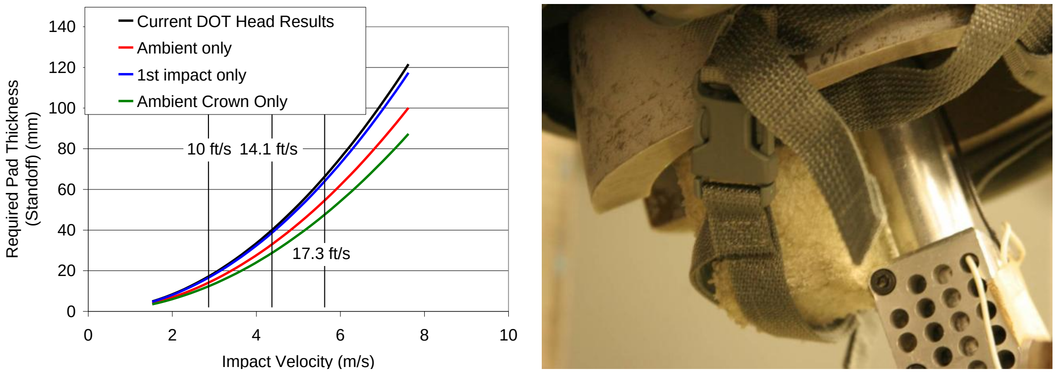

Figure 5. Tradeoff results on approximate pad thickness required to meet attenuation requirements by impact velocity (left), and chinform used during DOT and ISO headform testing (right)

4.3 The Effect of Shell Size, Headform Size, and Headform Fit

Some of the performance variation by helmet shell size is caused by differences in headform fit. Across all three headforms tested, at least two helmet sizes were fitted to the same sized headform for testing (size medium and large for all three headforms as well as size extra- and double extra-large for the DOT and the NOCSAE headforms). Since the helmet size is different and the headform size is not for such tests, there is the potential for a difference in performance between the two helmet sizes based upon headform fit. These differences in fit for one particular headform are independent of those for the alternative headforms; thus, some of the variation observed across helmet sizes by headform is due to varying degrees of headform fit. In other words, one helmet size may perform better than the other helmet size sharing the same sized headform because of fit; however, this same better performing helmet size may perform worse than its counterpart on a different headform type also because of fit.

Table 6 shows the mean peak accelerations across all tested conditions by helmet size, headform type, and headform size. In Table 6, the size “C” DOT headform, is used for both the size large and the size medium helmet. Likewise, the size “M” NOCSAE headform and the size “J” ISO headform are used for both the size large and the size medium helmet. Of the five helmet sizes, the medium helmet was the best performer at 169g on average for DOT headform tests. However, the medium helmet was the second worst performer at 118g on average for NOCSAE headform tests, and it was the median performer at 178g on average for ISO headform tests.

Another potential deviation in helmet performance by headform size is shown graphically in Figure 6. The ISO headform performs similarly to the DOT headform for all helmet sizes except the double extra-large. The double extra-large helmet had a different ISO headform size ("O") than that used on the extra-large helmet ("M"); however, the double extra-large helmet used the same size DOT headform as the extra-large helmet ("D"). The double extra-large helmet was the second best performing helmet size for the ISO headform and the worst performing helmet size on the DOT headform. These results are even more remarkable given the relative similarity in DOT and ISO headform performance for the remaining helmet sizes.

For the current study, the effect of shell size alone was not large for any of the headforms. However, the effect of matching shell size to headform size and anthropometry should be assessed independently of the other experimental variables. Headform fit may be a significant factor in the relative performance of helmet sizes, and future testing should examine headform fit more closely to ensure that unrealistic variation is not being included into blunt impact testing results. A quantitative comparison between typical headform to helmet fit and typical Soldier to helmet fit may provide the key insight needed to interpret and describe the degree of realism or lack thereof created in blunt impact testing by headform fit variation

Table 6. Mean peak acceleration across all velocity conditions for ambient temperature impacts only

Helmet Size	**DOT Headform**		**NOCSAE Headform**		**ISO Headform**	
	Size	***Avg Peak Acc. (g)***	***Size***	***Avg Peak Acc. (g)***	***Size***	***Avg Peak Acc. (g)***
XXL	D	216	L	99	O	170
XL	D	205	L	105	M	209
L	C	174	M	113	J	169
M	C	169	M	118	J	178
S	B	186	S	119	E	194

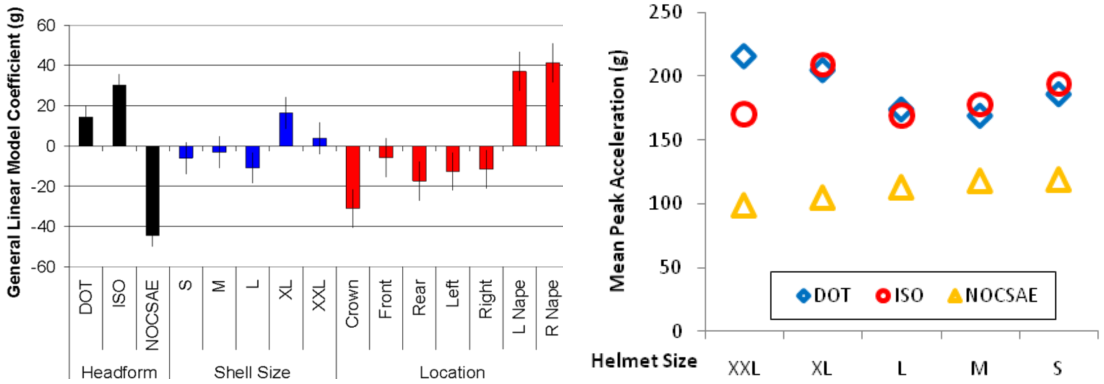

Figure 6. GLM results (left) and mean peak acceleration results by helmet size and headform type (right)

4.4 Impact Location, Headform Anthropometry, and Injury Assessment Values

The NOCSAE headform is more compliant than the ISO or the DOT headform; and, from the results, it is clear that under similar test conditions and impact energy the NOCSAE headform has the lowest peak accelerations in this study. Acceleration values found using the NOCSAE headform may represent a different potential for injury than the same value if found using the DOT or the ISO headform. Although the dramatic difference in measured accelerations under the same impact conditions is compelling evidence that the NOCSAE headform requires different injury criteria from those used with the ISO or DOT headforms, the injury criteria difference is not as simple as shifting the criteria by the average difference in measured accelerations. A significant portion of the acceleration difference recorded with the NOCSAE headform may be the result of better surface anthropometry in the nape region.

The DOT and ISO headforms may be erroneously predicting significantly higher injury risk at the nape locations due to poor surface anthropometry rather than due to a true increase in risk. The difference between the average nape DOT and the average nape NOCSAE headform acceleration for impacts of 3.0m/s and 5.3m/s is 21% and 88% of the NOCSAE headform acceleration for each velocity condition, respectively. In contrast, the average difference between DOT and NOCSAE headform accelerations for crown impacts of 3.0m/s and 5.3m/s is 20% and 16% of the NOCSAE headform acceleration for each condition, respectively. For impact locations such as the crown that have comparable anthropometric biofidelity between the NOCSAE and DOT headforms, the gap between measured headform acceleration is similar, by percentage. Regions, such as the nape, with poorer anthropometric biofidelity in the DOT headform than in the NOCSAE headform show a high degree of deviation, by percentage. This deviation is unrelated to the potential need for different injury assessment criteria for the two headforms. Careful consideration should be given to advantages and disadvantages of each test headform for future testing, and appropriate headform-specific injury assessment criteria should be used to evaluate results.

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