Proceedings of the ASME 2011 International Mechanical Engineering Congress & Exposition
IMECE2011
November 11-17, 2011, Denver, Colorado, USA

IMECE2011-64213

COMBAT HELMET-HEADFORM COUPLING CHARACTERIZED FROM BLUNT IMPACT EVENTS

Kimberly B. Vasquez
U.S. Army Aeromedical Research Laboratory
Fort Rucker, AL, USA

Katie P. Logsdon
U.S. Army Aeromedical Research Laboratory
Fort Rucker, AL, USA

Daniel B. Dorman
U.S. Army Aeromedical Research Laboratory
Fort Rucker, AL, USA

Valeta Carol Chancey
U.S. Army Aeromedical Research Laboratory
Fort Rucker, AL, USA

ABSTRACT

Observed head injury has historically been mechanically related to headform center of gravity (CG) acceleration. Helmets (motorcycle, sports, military, etc.) are evaluated based on the headform CG peak acceleration for blunt impacts. However, recent interest has shifted to collecting data from the helmet shell itself, as it is an optimal location for mounting sensors due to ease of access, sufficient surface area availability, and limited interference to the wearer.

In order to accurately predict head injury from data collected on the helmet shell, the helmet and headform must be rigidly coupled. Headform-helmet fit typically is dependent on the pad fitting system and the person mounting the helmet to the headform because a standard states which headform to use. The objective of this study is to compare the Department of Transportation (DOT) headform (currently used in military blunt impact testing) to the more anthropomorphic International Standard Organization (ISO) half headform.

Testing was completed on a monorail drop tower to analyze the effect of helmet/headform coupling on the blunt impact behavior of ACH helmets using FMVSS test methodology. Three headform configurations were used: the DOT headform (standard for military helmet blunt impact testing) with required surrogate chin, the ISO half headform (standard for ASTM helmet testing), and the ISO half headform with a surrogate chin. The two currently field-approved pad types were also used to determine best headform-helmet fit. Results from these series of tests will be presented, including headform peak acceleration and relative motion between the helmet and headform.

INTRODUCTION

Head injury metrics are commonly defined using headform center of gravity (CG) acceleration data. Head injury metrics like peak acceleration, the Head Injury Criteria (HIC), and the Gadd Severity Index (SI) are measured and/or calculated from headform acceleration and duration of impact [1] [2]. As the testing standards for helmet protection performance have evolved, these head injury criteria have continued to be used to evaluate helmets. Multiple standards (FMVSS, ASTM, ANSI) and recommendations (Snell) are now available and all define helmet blunt impact protection using various headform CG acceleration criteria [3]. Each standard designates its own methods and test equipment: a drop tower (monorail or twin-wire), headform (DOT, ISO, NOCSAE), headform CG accelerometer (single or triaxial), and a velocimeter to evaluate the dynamic event. Choosing the proper standard depends upon the type of helmet (motorcycle, sports, military, etc.) being evaluated [4] [5] [6] [7].

The Army's Advanced Combat Helmet (ACH) is evaluated according to the FMVSS 218 [8], with modifications specific to the military environment. The blunt impact evaluation requires the DOT headform with a single-axis accelerometer at the headform CG. USAARL supplements the FMVSS218 standard by collecting impact surface force data from a load cell mounted below the impact anvil. Recent testing has revealed a discrepancy in the impact surface force time trace. For a single event, the headform-based data contained a single peak in the acceleration time trace, while the surface impact force time trace revealed two distinct peaks for that same event. High speed video was taken of another helmet test event. The high speed video confirmed two distinct impacts onto the force plate: (1) the helmet impacted the anvil and rebounded to

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **NOV 2011**	2. REPORT TYPE	3. DATES COVERED **00-00-2011 to 00-00-2011**

4. TITLE AND SUBTITLE **Combat Helmet-Headform Coupling Characterized from Blunt Impact Events**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Aeromedical Research Laboratory,Fort Rucker,AL,36362**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Observed head injury has historically been mechanically related to headform center of gravity (CG) acceleration. Helmets (motorcycle, sports, military, etc.) are evaluated based on the headform CG peak acceleration for blunt impacts. However, recent interest has shifted to collecting data from the helmet shell itself, as it is an optimal location for mounting sensors due to ease of access, sufficient surface area availability, and limited interference to the wearer. In order to accurately predict head injury from data collected on the helmet shell, the helmet and headform must be rigidly coupled. Headform-helmet fit typically is dependent on the pad fitting system and the person mounting the helmet to the headform because a standard states which headform to use. The objective of this study is to compare the Department of Transportation (DOT) headform (currently used in military blunt impact testing) to the more anthropomorphic International Standard Organization (ISO) half headform. Testing was completed on a monorail drop tower to analyze the effect of helmet/headform coupling on the blunt impact behavior of ACH helmets using FMVSS test methodology. Three headform configurations were used: the DOT headform (standard for military helmet blunt impact testing) with required surrogate chin, the ISO half headform (standard for ASTM helmet testing), and the ISO half headform with a surrogate chin. The two currently field-approved pad types were also used to determine best headform-helmet fit. Results from these series of tests will be presented, including headform peak acceleration and relative motion between the helmet and headform.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**9**	

reconnect with the headform; and then (2) the coupled helmet/headform assembly impacted the anvil together.

This phenomenon required additional investigation to understand the separation and relative motion between the helmet and headform in laboratory testing. Such de-coupling of the helmet/headform is of particular interest due to ongoing operational and research efforts that are collecting helmet shell exposure data to develop and validate improved head injury metrics, including those criteria based on CG acceleration. Several parameters affect the ACH blunt impact performance as measured by the headform CG acceleration. This study uses ACH blunt impact test methodology to investigate the effect of headform type and pad fitting system on helmet/headform coupling as demonstrated in headform CG acceleration data, surface impact force data, and relative displacement from high speed video analysis.

METHODS

The test procedure was performed in accordance with the Federal Motor Vehicles Safety Standard (FMVSS) 218 DOT 2006, and has been modified for the specific needs of the test series for impact site and subsequent impacts of military combat helmets (CO/PD-05-04) [9]. FMVSS 218 provides the regulations for the test drop tower (Fig. 1), headforms, impact surfaces, and the data collection standard as specified by the Society of Automotive Engineers (SAE) Standard J211 [10]. A Denton barrier load cell 4773S1 was used to collect triaxial surface impact forces onto the 1.9-inch radius hemispherical impact anvil used in all tests. The transmitted headform acceleration was measured with an Endevco 7264B-500T single-axis accelerometer located at the headform CG. The acceleration and force data were filtered according to SAE J211, CFC 1000 and CFC 600 respectively. The headforms used for this testing were the DOT size "C" headform (Fig. 2) and the International Standards Organization (ISO) size "M" headform (Fig. 3). The DOT headform lacks sufficient anthropomorphic features to attach the helmet chinstrap. In order to overcome this, the ACH standard requires use of a surrogate foam chin in military testing. Since the ISO headform has the anthropomorphic feature to secure the chinstrap, it was tested with and without the surrogate foam chin.

Six large Mine Safety Appliances (MSA) ACH's were tested with the two combat approved fitting pad systems (A and B). Both of these approved pads are distributed as 0.75-inch thick pads. Pad type A is composed of two layers of viscoelastic foam. The layer closest to the head is a low density comfort layer; the other is higher density for increased impact energy attenuation. Pad type B contains two foam materials. The layer closest to the head is an open cell "comfort" pad. The energy attenuating layer, closest to the helmet shell, is a patented class of material defined as porous closed-cell composite, formed by fusing together closed cell polymer beads at their tangent points [11].

The test matrix for all the helmet configurations is shown in Table 1. All data was collected at 20,000 Hz using a TDAS G5 (DTS, Inc.) and anti-aliased at 3,000 Hz.

Table 1: ACH test matrix and sample size.

Headform	Pad Type	Impact Velocity (10.00 fps)
DOT size "C"	A	1
	B	1
ISO size "M"	A	1
	B	1
ISO size "M" with chin (ISOC)	A	1
	B	1
Total Number of Helmets		6

Figure 1: An ACH blunt impact evaluation in the crown impact location on the monorail drop tower.

Figure 2: The DOT size "C" headform is the military standard for blunt impact testing of the size large ACH.

Figure 3: The ISO size "M" headform (used to fit the large ACH) is the standard for blunt impact testing of bicycle and motorcycle helmets.

Six helmets were used in this assessment on each of the headform configurations. Each helmet was exposed to 14 blunt impacts (2 impacts at each of 7 impact sites). The second impact immediately followed the first impact within a 2-minute period. The helmet impact sites include the crown, front, left, right, rear, left nape, and right nape. These impact sites and headform orientations are illustrated in figure 4. One impact velocity, 10.00 feet per second (fps), with an allowable tolerance of ±3% was evaluated.

Figure 4: Helmet impact sites are highlighted for the Crown, Front, Right, Rear, and Right nape locations. Left and Left nape locations are symmetric to the Right.

Helmets were mounted to the headform, and the combined helmet/headform assembly was raised to the drop height necessary to achieve the predetermined impact velocity. Impact velocity, headform acceleration, surface impact force, and high speed video were collected for each test. After each test, each helmet was thoroughly inspected for loose components and distorted hardware. If necessary, the helmet was repositioned on the headform between the two impacts at a single helmet impact site. When the headform was repositioned for the next helmet impact site, the helmet was removed and then mounted again onto the headform. Throughout testing, a single individual, the test engineer, mounted the helmet onto the headform to ensure a consistent helmet-headform interface (fit and tightness of the retention system).

A Phantom v5.0 HSV camera by Vision Research was used to capture the impact. The camera was placed 4-feet away from the impact, perpendicular to the z-axis, as described by SAE J211, and parallel to the plane of impact. Video was collected at 1000 frames per second. High intensity lighting was used for contrast in addition to a black and white checkerboard background. The Phantom and DTS data were synched in time using a TTL from the velocimeter. Image Systems TEMA 2D Motion 3.1 was used to track fiduciary markers placed on the test apparatus: 2 markers on the helmet, 1 marker on the follower, 1 marker on the ball arm, and 2 reference markers separated by a known distance on the load cell (Fig. 1).

RESULTS

Forty-two impact conditions were tested resulting in eighty-four impacts with data lost on one impact.

ACH pass criteria

The pass criteria for an ACH and the pad system states that no individual peak acceleration shall exceed 150 Gs at a 10.00 fps impact (using the DOT headform) [4]. Both pad types in this test series are currently approved for operational use, and therefore were expected to pass at all locations on the DOT headform at 10.00 fps. Only left and right napes of pad B on the ISO and ISOC configurations did not pass the criteria. The impact locations that passed the criteria for each headform, pad type, and impact velocity are shown in Table 2.

Table 2: Impact locations that met the pass criteria of the ACH and pad system (every impact ≤150G)

Headform	Pad Type	Test impact velocity (10.00 ± 0.3 fps)
DOT	A	All locations passed
	B	All locations passed
ISO	A	All locations passed
	B	Crown, front, left, right, and rear passed
ISOC	A	All locations passed
	B	Crown, front, left, right, and rear passed

Acceleration and Force time traces

Headform acceleration and surface impact force was collected for each impact. The acceleration time trace contains one peak, while the force time trace contains two distinct peaks for the same event. Figures 5 through 7 are representative samples of this phenomenon. Force traces from the load cell were not mass compensated, and therefore not used for additional analysis.

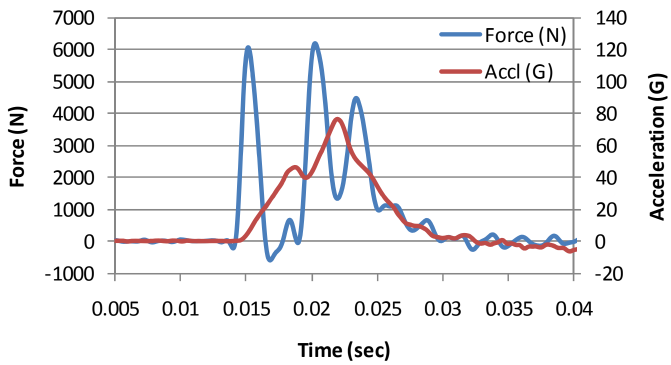

Figure 5: DOT, Pad B, Crown impact force and acceleration time traces.

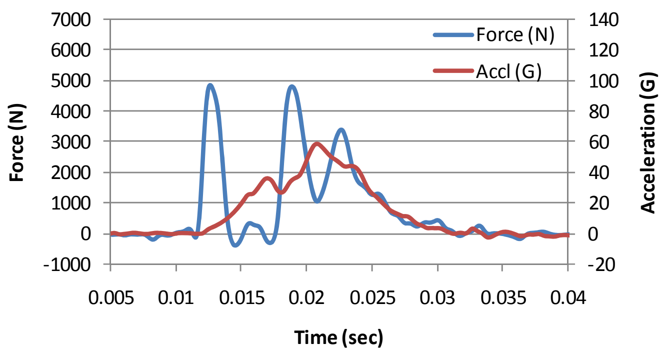

Figure 6: ISO, Pad B, Crown impact force and acceleration time traces.

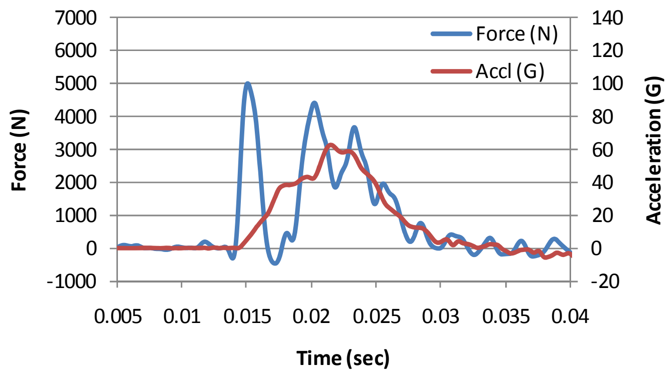

Figure 7: ISOC, Pad B, Crown impact force and acceleration time traces.

The first force peak is the helmet making contact with the anvil. As the first force peak returns to zero, the helmet is rebounding. While the helmet is rebounding, the headform continues to fall as shown by the increase in acceleration. The headform and helmet re-couple and continue to fall to impact where peak acceleration is reached.

Displacement and relative motion

TEMA 2D was used to track position, velocity, and acceleration of two helmet markers, one follower marker, and one ball arm marker. Because the headform is considered to be rigidly mounted to the ball arm and follower, we assumed the follower data to be representative of the headform. For each impact, the time trace of the tracked data for the raw position of the follower-headform and helmet markers was examined (Fig. 8). The initial helmet impact position was then determined and all other data was normalized to this point for each impact (Fig. 9). The follower-headform position demonstrates approximately 0.75-inch of continued movement (relative motion) after the initial helmet impact (Fig. 10).

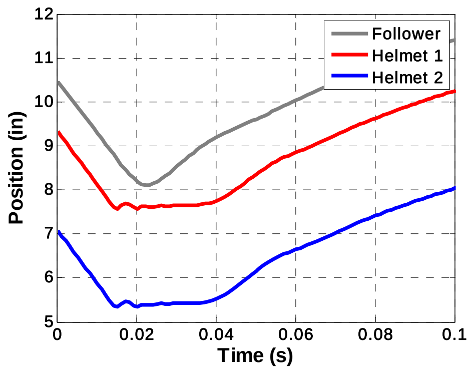

Figure 8: Raw position TEMA tracked data of the follower and 2 helmet markers of a DOT, Pad B, Crown impact are shown.

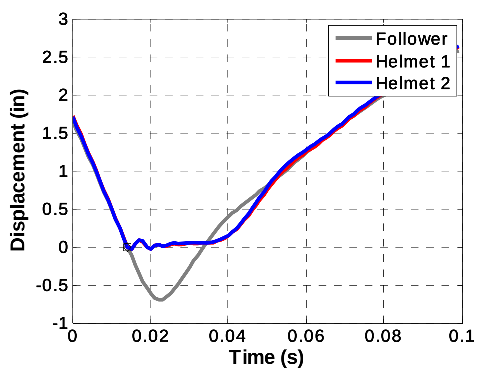

Figure 9: As the data from Figure 8 is aligned at point of helmet impact on the anvil, the follower (headform) continues to move down while the helmet rebounds and impacts the anvil a second time just before the follower impacts the anvil at approximately 0.02 seconds.

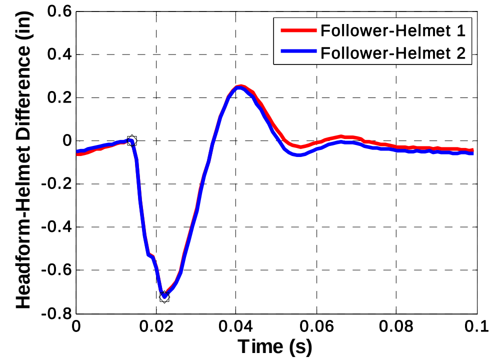

Figure 10: Relative motion between the follower, representing the headform movement, and the helmet exhibits approximately 0.75 in continued movement after initial helmet impact.

The nominal pad thickness for each pad type is 0.75-inch. Any relative motion between the headform and helmet greater than or equal to 0.75-inch suggested additional separation between the headform and pad. A representative sample of pads was measured in the lab: Pad A was 0.7-inches thick and Pad B was 0.85-inches thick. The relative motion for each impact was normalized to its respective pad type (Fig. 11 and 12). Mean and standard deviations were calculated and are shown in Tables 3 and 4.

Table 3: Measured relative displacement as a percentage of actual pad thickness by headform and pad type.

Headform and Pad type	Mean	Std Dev
DOT Pad A	80%	12%
ISOC Pad A	69%	8%
ISO Pad A	71%	5%
DOT Pad B	81%	18%
ISOC Pad B	70%	11%
ISO Pad B	70%	19%

Table 4: Measured relative displacement as a percentage of actual Pad thickness by impact location, Pad type, and drop number (regardless of headform configuration).

Impact Location	Mean	Std Dev
CR Pad A 01	68%	7%
FR Pad A 01	78%	5%
LF Pad A 01	82%	18%
LN Pad A 01	73%	3%
RN Pad A 01	71%	11%
RR Pad A 01	71%	11%
RT Pad A 01	74%	10%
CR Pad A 02	69%	7%
FR Pad A 02	78%	4%
LF Pad A 02	82%	13%
LN Pad A 02	71%	14%
RN Pad A 02	67%	5%
RR Pad A 02	68%	8%
RT Pad A 02	76%	15%
CR Pad B 01	93%	11%
FR Pad B 01	76%	2%
LF Pad B 01	88%	18%
LN Pad B 01	56%	11%
RN Pad B 01	63%	35%
RR Pad B 01	79%	12%
RT Pad B 01	67%	10%
CR Pad B 02	92%	8%
FR Pad B 02	75%	1%
LF Pad B 02	84%	10%
LN Pad B 02	57%	7%
RN Pad B 02	62%	22%
RR Pad B 02	76%	7%
RT Pad B 02	64%	6%

The DOT headform has the most relative displacement, regardless of pad type. The ISOC configuration has the least variation in relative displacement for Pad Type B. The ISO configuration has the least variation in relative displacement for Pad Type A. Pad Type A demonstrates the least variation overall. The front impacts show the least variation between headforms and pad types. The nape impacts are more consistent between left and right sides for Pad Type A than Pad Type B.

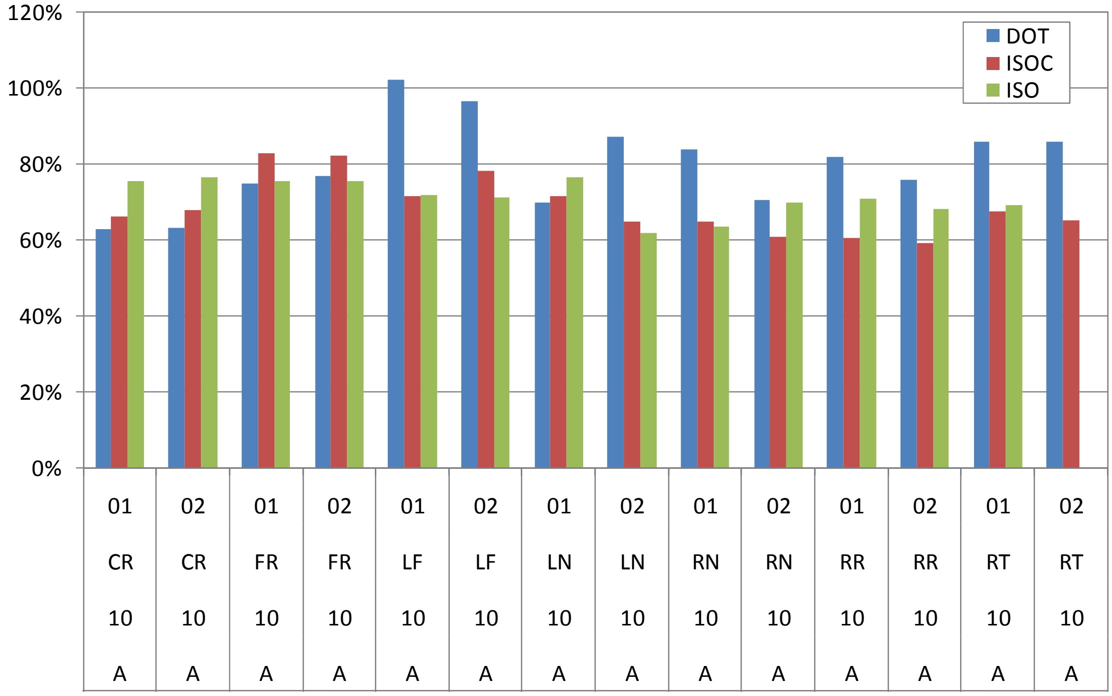

Figure 11: Measured relative displacement as a percentage of actual Pad A thickness (0.7-inch).

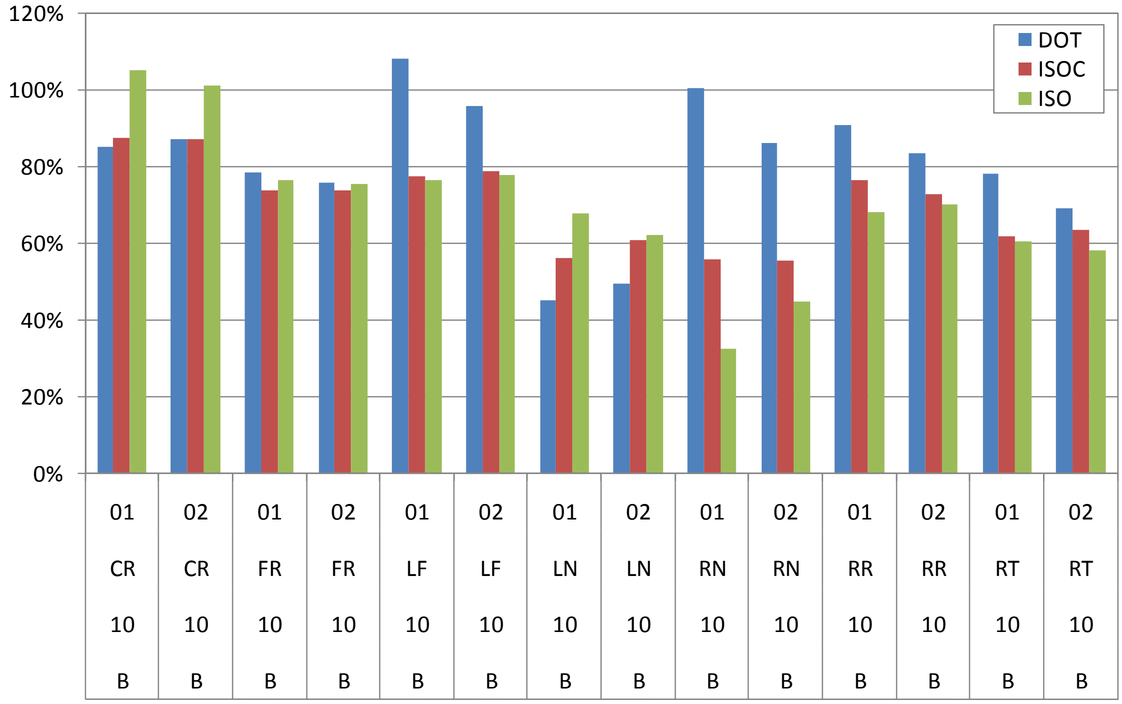

Figure 12: Measured relative displacement as a percentage of actual Pad B thickness (0.85-inch).

DISCUSSION

In this study, we performed multiple blunt impact tests using the ACH blunt impact test methodology as described in the Army Purchase Description (CO/PD-05-04) [9]. Within this methodology, we used two industry standard impact headforms and two Army approved ACH pad types. Despite using industry practices and standard approved equipment and materials, variability was observed in the headform CG acceleration, which is an important basis for head injury metrics.

Specifically, the unique geometries of the headforms used had various effects on headform/helmet coupling and acceleration. The nape impact location of the ISO headform configurations were the only impacts to not pass the blunt impact evaluation criteria (less than or equal to 150 G). This was likely due to the more pronounced curvature of the ISO headform by creating a point load at the impact site. Additionally, tears in the oblong pads in the rear of the helmet were observed after the nape impacts. Low variation in measured relative displacement in the front impacts may be due to similar curvature of the DOT and ISO headforms. The ISO headform configurations showed lower relative displacement, indicating a potential tighter coupling between the helmet and headform.

The headform coupling contribution was confounded due to variation in the approved pad types. Both of these approved pads are distributed as 0.75-inch thick pads and commonly thought to provide equivalent stand-off distance between the head and helmet shell. Pad type A had a measured thickness of 0.70-inch, 2- 0.35-inch thick layers. Pad type B had a measured thickness of 0.85-inch: a 0.25-inch thick layer and a 0.6-inch thick layer.

Several limitations of this study were due to minimal instrumentation required by the industry standards for helmet blunt impact evaluations. The study added 2D high speed video and recorded surface impact force. The 2D high speed video was able identify relative in-plane motion. Out-of-plane helmet flexion and helmet rotation were observed. High speed video collected in 3D would allow us to measure flexion and rotation of the helmet shell on the headform during an impact. Other instrumentation that could have provided additional insight includes the use of pressure film, which could be used to determine initial coupling of the helmet and headform. Improved initial fit minimize helmet/headform separation and limit the observed relative displacement to the pad type variable alone. Improvements in data acquisition and pressure film technology may also provide the ability to dynamically measure and record contact pressures throughout the impact sequence. In-progress studies will collect accelerations of the helmet shell at high-rate (50,000+ Hz) to characterize the difference in headform response and helmet response to an impact.

CONCLUSIONS

De-coupling of the helmet/headform is of particular interest due to ongoing operational and research efforts that are collecting helmet shell (including football, hockey, and military) exposure data. The collection of helmet shell exposure data has prompted the need to develop a relationship between head CG acceleration (current head injury metric) and helmet shell acceleration during a dynamic event.

This laboratory testing has shown that a direct relationship will have many contributing factors. For instance, simple blunt exposures can cause the helmet to receive two impacts while the headform only receives one. Other variables to consider are: helmet manufacturer, pad manufacturer, and goodness of fit. Fit is dependent on headform, pad, and retention system. Another issue is the preload on the pads from the tightness of the retention system.

To reduce the variability in goodness of fit, further research is required to develop or evaluate updated anthropometric and anthropomorphic headforms that include a chin and nape. Additionally, investigations are needed to develop a standard methodology for realistically and consistently coupling the combat helmet to the headform.

ACKNOWLEDGMENTS

This work was funded through the AMEDD Advanced Medical Technology Initiative (AAMTI) supported by the Telemedicine and Advanced Technology Research Center (TATRC) for the project titled, “Evaluation of Helmet Impact Indicator as Potential Head Injury Indicator.”

DISCLAIMER

The views, opinions, and/or findings contained in this paper are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designate by other official documentation. Citation of trade names in this paper does not constitute an official Department of the Army endorsement or approval of the use of such commercial items.

REFERENCES

[1] Chou, C.C. and Nyquist, G.W. Analytical Studies of the Head Injury Criterion (HIC). Presented at SAE, Detroit, MI, 25 February – 1 March 1974.

[2] Gadd, C.W. Use of a Weighted-Impulse Criterion for Estimating Injury Hazard. Proceedings: Tenth Stapp Car Crash Conference, Holloman AFB, NM, 8-9 November 1966.

[3] Yoganandan, N. et al. (Eds.) 1998. Frontiers in Head and Neck Trauma Clinical and Biomedical. Amsterdam; IOS Press.

[4] Smith, T.A., Tees, D., Thom, D.R., and Hurt, H.H. Jr. 1994. Evaluation and replication of impact damage to bicycle

helmets. *Accident Analysis & Prevention.* Dec; 26(6): 795-802.

[5] Viano, D.C., Pellman, E.J., Withnall, C., and Shewchenko, N. 2006. Concussion in professional football: performance of newer helmets in reconstructed game impacts--Part 13. *Neurosurgery*. Sep; 59(3):591-606.

[6] Williams, M. 1991. The protective performance of bicyclists' helmets in accidents. *Accident Analysis & Prevention*. Apr-Jun;23(2-3):119-31.

[7] McEntire, B.J. and Whitley, P. 2005. Blunt Impact Performance Characteristics of the Advanced Combat Helmet and the Paratrooper and Infantry Personnel Armor System for Ground Troops Helmet. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Report No. 2005-12.

[8] U.S. Department of Transportation. Federal Motor Vehicles Safety Standard 218. Sec. 571.218, Standard No. 218, FMVSS 218 - 49 CFR 571.218.

[9] Department of the Army. 2007. Purchase Description Helmet, Advanced Combat (ACH), CO/PD-05-04. Fort Belvoir, Virginia: Project Manager – Soldier Equipment, Program Executive Office - Soldier.

[10] Society of Automotive Engineers. 1995. Recommended Practice J211-1. Instrumentation for impact test – Part 1 – Electronic instrumentation. Warrendale, PA.

[11] McEntire, B.J. and Padgett, K.L. 2007. Blunt Impact Performance of the US Marine Corps Light Weight Helmet (LWH) and the US Army Advanced Combat Helmet (ACH) with Fielded and Alternative Fitting Systems. Fort Rucker, AL: U.S. Army Aeromedical Research Laboratory. USAARL Technical Memorandum No. 2007-04.