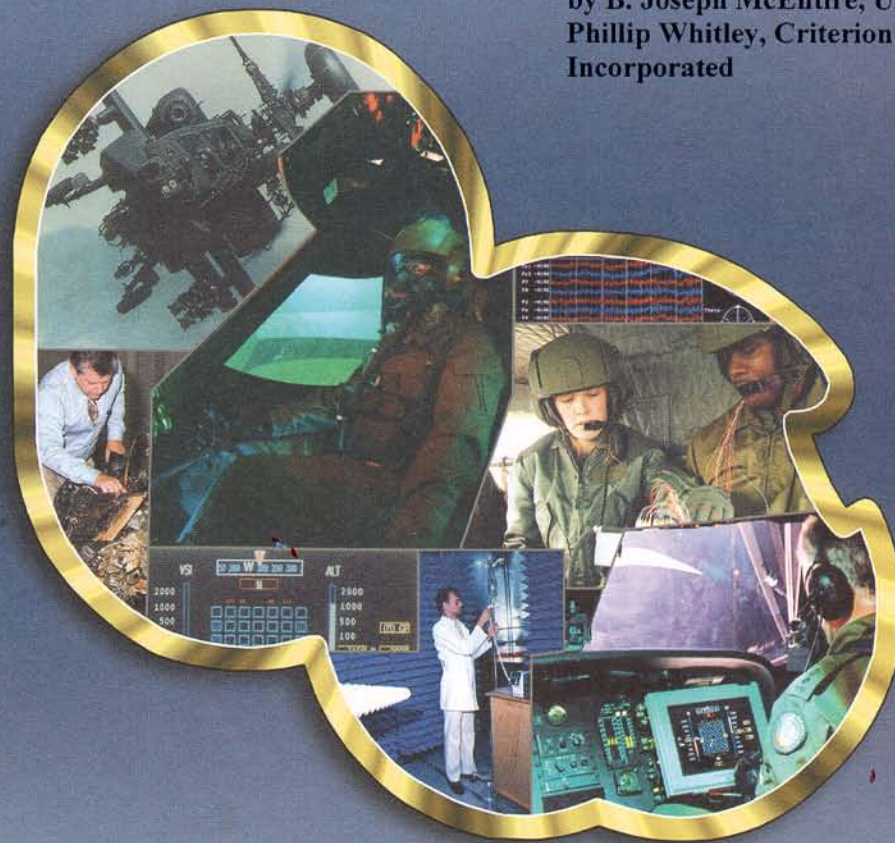


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Blunt Impact Performance Characteristics of the Advanced Combat Helmet and the Paratrooper and Infantry Personnel Armor System for Ground Troops Helmet

by B. Joseph McEntire, USAARL, and
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Incorporated



Aircrew Protection Division

August 2005

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Background

Combat soldiers operate in a diverse range of operational environments and injury threats. These operational environments and injury threats place demands on protective systems to provide consistent protective performance throughout an expected range of temperature and threat magnitude. Protective helmets are no exception. The Advanced Combat Helmet (ACH) is configured with fitting pads that possess the capability to attenuate blunt head impact forces. Previous combat helmets, such as the Personnel Armor System for Ground Troops (PASGT) and the older M-1 “steel pot,” were not required by their governing specifications to provide any tested levels of blunt impact protection.

Protective helmets are typically required to absorb energy in order to reduce head injury risk during blunt impact events. The energy-absorbing mechanism must be robust enough to reduce the impact energy to a low injury probability level throughout a realistic range of impact velocities and environmental temperatures, regardless of the helmet impact site. To obtain further information on the blunt impact performance characteristics of U.S. Army combat helmets, a series of blunt impact tests were conducted with the ACH and the paratrooper and infantry versions of the PASGT helmet. Each helmet type was tested at two impact velocities, three environmental temperatures, and seven impact sites with two successive impacts. The performance of each was characterized by the transmitted acceleration measured within a standard head form and compared against the recommended threshold for mean and maximum acceleration.

Military relevance

In considering the Army operational environments, three head impact threat conditions are easily recognized. The first is involvement in a motor vehicle accident. If the infantry helmet possesses impact attenuation capabilities, head injury mitigation could be realized during motor vehicle accidents. The second condition is tripping and falling while maneuvering by foot. A simple slip or fall can lead to a head impact. The last condition is the parachutist, or airborne environment.

Airborne operations regularly expose paratroopers to risk of head impact during flight (unexpected turbulence or evasive maneuvers), aircraft exit (impact with the door frame or fuselage), descent (riser slap or collision with other jumpers), the parachute landing fall (PLF), and after landing (obstacle strikes during dragging in high winds). Pascal et al. (1990) conducted an epidemiological review of paratrooper injuries reported on DA Form 285 “U.S. Army investigation accident report” for the period of 1985 to 1989. During this period, 277 paratroopers suffered head injuries that resulted in at least one lost work day and four died as a result of their injuries. Most injuries occurred during the landing phase (77.8%) and 89.4% involved concussion or brain contusion. Craig and Morgan (1997) reviewed paratrooper injuries occurring at Fort Bragg, NC, between May 1993 and December 1994 and recorded an overall military parachute injury rate of 8 injuries per 1000 aircraft exits, with head injuries accounting for 18.4% of the casualties.

Regardless of the operational environment, even relatively mild head impacts, while not life threatening, can cause short-term impairment from dizziness, headaches, memory loss, lack of ability to concentrate, and irritation. Given the necessity for speed, aggressiveness, and responsiveness on the battlefield, these symptoms become militarily significant, no matter how temporary, by seriously jeopardizing soldier survivability and the success of the unit's mission. There is an obvious need to protect the individual soldier and reduce the injury rate to a minimum, primarily to preserve the efficiency of the fighting unit for combat, but also because a high injury rate would have a detrimental effect on morale, recruiting, etc. (Davison, 1990).

Methods and materials

Helmets

Three helmet configurations were evaluated. These included the ACH, shown in Figures 1 and 2, and two PASGT helmets, the infantry and paratrooper configurations, as shown in Figures 3 and 4. All helmets were obtained from either the Natick Soldier Center or the U.S. Army supply system. Each helmet system was assembled and fitted according to the appropriate military guidance document (Natick Pamphlet 70-2 [2000], and TM 10-8470-204-10, [2004]). The ACH fitting pads were installed in the "standard" configuration as outlined in TM 10-8470-204-10.

The test head form measured 7-15/16 inches in length, 5-15/16 inches width, and 22-3/4 inches in circumference. These head form measurements suggest the proper size helmet is large for both the ACH and PASGT helmets. All the ACH helmets were configured with the size 6 fitting pads. The seven fitting pads were positioned in accordance with the standard placement locations for initial fitting and for airborne and other high-risk operations. The PASGT helmet in the standard infantry configuration included the web and leather headband, and the web cradle straps. The paratrooper PASGT configuration (Figure 5) included the nape strap, the rear nape pad, and the optional and available Parachutist Impact Liner (PIL). At the area where the PIL and parachutist nape pad overlap, the PIL material was removed along the perforated edge as this is an authorized alteration and would reduce impact protection.



Figure 1. External views of the ACH helmet.



Figure 2. Internal view of the ACH configuration and components.



Figure 3. External views of the PASGT helmet.



Figure 4. Internal view of the PASGT infantry helmet.

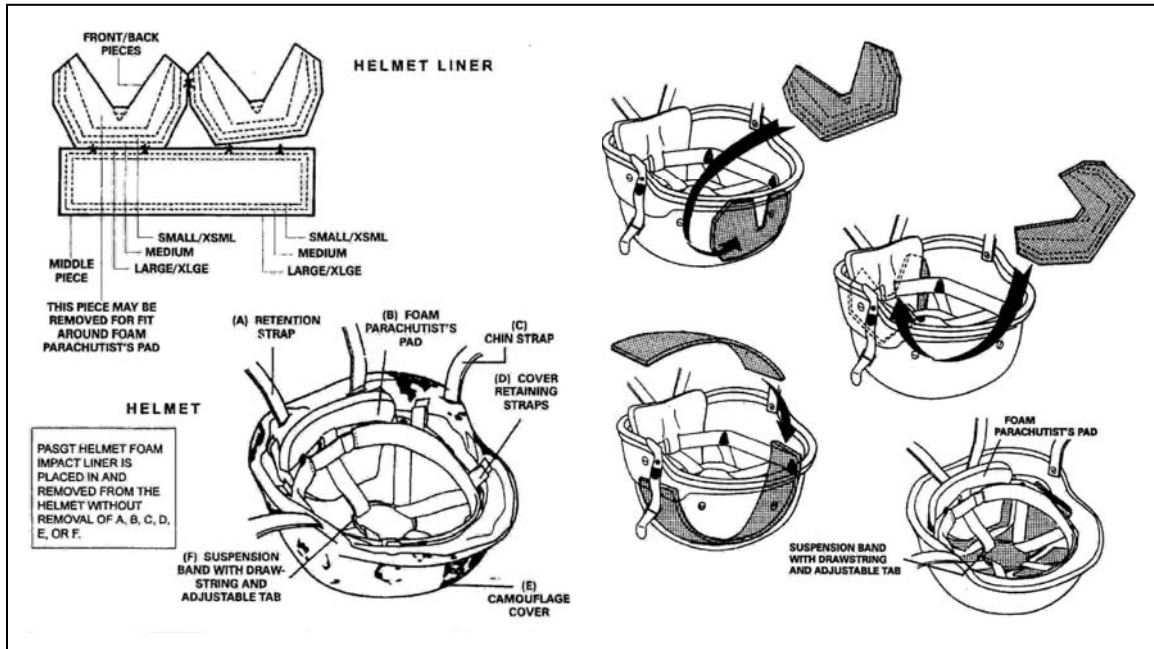


Figure 5. Assembly illustration of the paratrooper PASGT helmet configuration with the PIL, parachutist nape pad, and nape strap.

Helmet impact test procedure

The test procedure was performed in accordance with the Federal Motor Vehicles Safety Standard (FMVSS) 218 (U.S. Department of Transportation), for motorcycle helmets modified for the specific needs of the test series for impact site, test temperature and subsequent impacts. FMVSS 218 describes the test fixture, head forms and impact surfaces and the data collection standard, Society of Automotive Engineers (SAE) Standard J211 (1995). The transmitted acceleration was measured with a single-axis accelerometer located at the center of gravity of the head form. The hemispherical impact anvil and the size “C” FMVSS 218 head form were used in all tests. Nine helmet samples of each type were tested at each impact velocity; three of each helmet type were conditioned to three environmental conditions. These environmental conditions were an ambient temperature of $70^{\circ} \pm 5^{\circ}\text{F}$, a cold temperature of $14^{\circ} \pm 5^{\circ}\text{F}$, and a hot temperature of $130^{\circ} \pm 5^{\circ}\text{F}$. Helmets were environmentally conditioned a minimum of 4 hours prior to testing. The hot and cold environmental impacts at each impact location (first and second impacts) were conducted within 5 minutes after helmet removal from the conditioning chamber. The helmets were returned to the conditioning chamber and exposed for at least 15 minutes before removal for another test impact location.

Since the ACH helmet fitting pads are less compliant (i.e., more rigid) when exposed to cold temperatures, the cold-conditioned ACH helmets were pre-fitted onto spare test head forms identical or similar to the FMVSS size C head in the conditioning chamber. Otherwise, these

helmets could not be properly positioned on the test head form and tested within the 5 minute time requirement.

A total of 18 helmets of each configuration were used in this assessment. Each helmet was exposed to 14 blunt impacts -- 2 impacts at each of the 7 impact locations. Each impact site was exposed to a second impact immediately following the first impact, within a 2-minute period. The permissible impact locations, shown in Figure 6, included the front, back, left side, right side, lower left nape, lower right nape, and the crown. These impact sites are summarized in Table 1. Two impact velocities, 10 and 14.14 feet per second (fps), with a tolerance of $\pm 3\%$, were used to determine the energy attenuation of the helmets at the various combinations of helmet type, impact site, and environmental temperature.

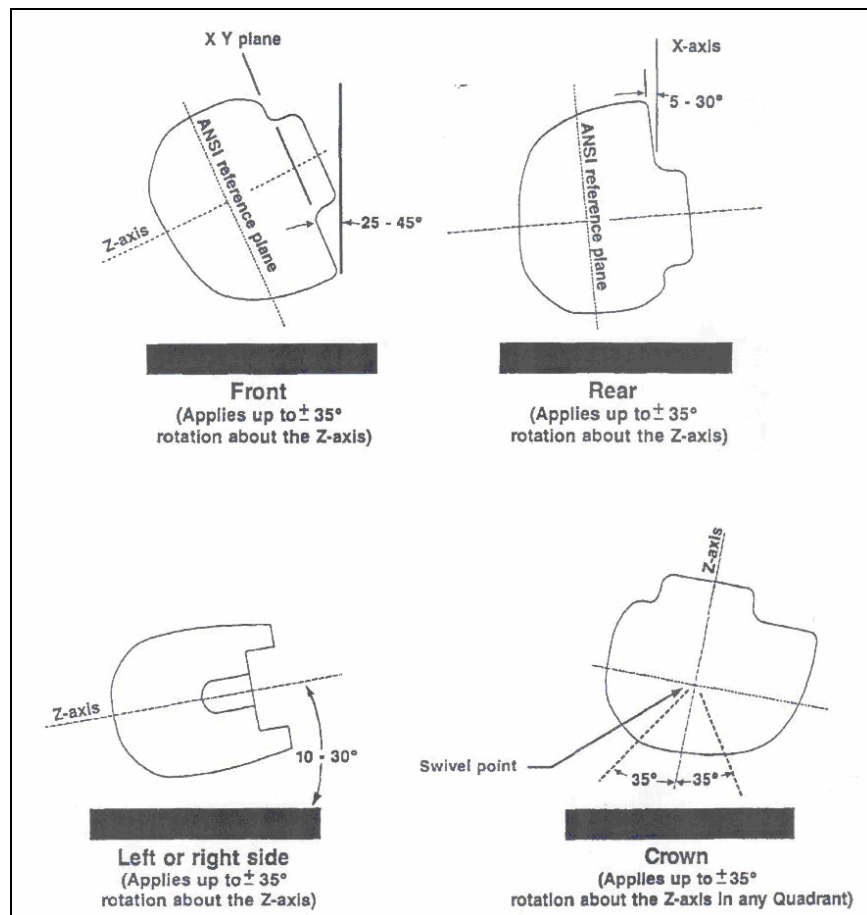


Figure 6. Test head form orientations for impact testing.

Table 1.
Head form orientations during blunt impact testing.

Impact site	Permissible headform base orientation	Actual headform base orientation
Front	25 - 45 degrees off vertical	25 degrees off vertical
Rear	5 - 30 degrees off vertical	25 degrees off vertical
Left or right side	10 - 30 degrees off vertical	25 degrees off vertical
Crown	+/- 35 degrees off horizontal	10 degrees off horizontal
Left or right nape	0 degrees off vertical, rolled 15 to 35 degrees left or right	0 degrees off vertical, rolled 30 degrees

Combat helmet impact acceleration threshold

Historically, there has not been a blunt impact protective requirement for combat helmets. For airborne operations, ½-inch thick Vinyl Nitrile foam pads are required in the PASGT helmet nape area to provide protection during rearward parachutist landing fall. The PIL was introduced into the Army inventory for use by airborne troops with the PASGT helmet, but its use is optional. Neither the nape pad nor the PIL were developed with established performance thresholds.

Protective helmets used by Army aviators and civilian motorcycle riders have blunt impact performance thresholds. The motorcycle helmet industry adopted standards that provide a minimum level of head protection during accidents. Early motorcycle helmet standards established a peak head form acceleration limit of 400 G as the pass-fail criteria. The 400 G threshold is considered to be the limit for serious head and brain injury. Interpretation of this requirement is that any helmet test producing a head form acceleration greater than 400 G is a failure.

This acceleration threshold was fundamentally based on cadaver head impact research results conducted by Wayne State University (Patrick, Lissner, and Gurdjian, 1963). The result of this research was a head acceleration tolerance curve, shown in Figure 7, which suggested an acceleration and time dependency relationship. Basically, the greater the acceleration level experienced by the head, the shorter the time duration that it can be tolerated before injury. The FMVSS 218 incorporates time dependency into their standard. The FMVSS 218 headform acceleration limits are shown in Table 2.

Also included in Table 2 are the acceleration requirements for other protective headgear standards. The ANSI had a standard for protective headgear for motor vehicular users (ANSI Z90.1-1992) (1992) with an acceleration limit of 300 G peak, but this standard was not renewed and has expired. The Snell Memorial Foundation (2000) established a standard for protective headgear for use with motorcycles and other motorized vehicles, also with a 300 G peak acceleration as a performance limit.

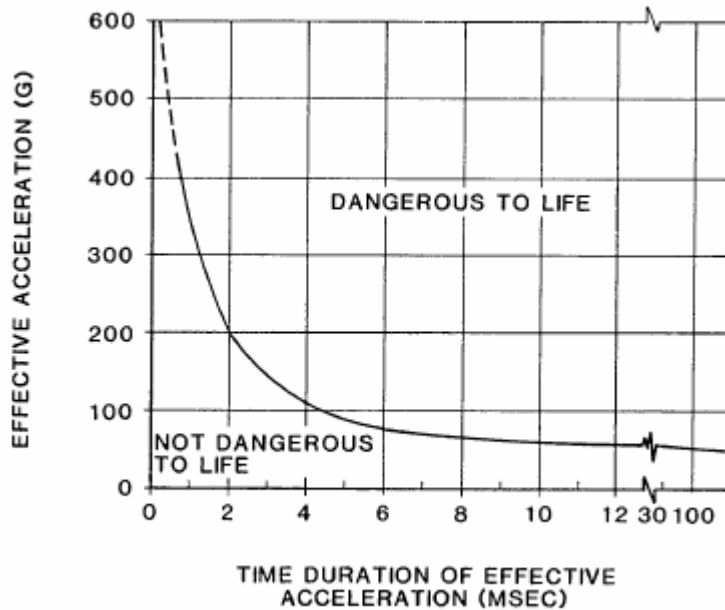


Figure 7. Wayne State tolerance curve for the human brain in forehead impacts against plane, unyielding surfaces.

Table 2.
Protective helmet impact test standards and acceleration thresholds.

Reference standard	Acceleration level (G)	Time limit	Impact locations
FMVSS 571.218	400	Peak	All
	200	2.0 ms	
	150	4.0 ms	
ANSI-Z90.1	300	Peak	All
Snell 2000	300	Peak	All
U.S. Army aviator helmet (HGU-56/P)	175	Peak	Headband
	150	Peak	Crown & earcups

The U.S. Army SPH-4 aviator helmet standard (MIL-H-43925) (Department of the Army, 1980) based the blunt impact protection on the ANSI Z90.1 standard. Analysis of helmets recovered from U.S. Army aviation accidents, and the wearer head injury, suggested impact protection improvements should be made. Based on accident helmet damage reconstruction efforts, Slobodnik (1980) concluded that the pass-fail criteria was too high and suggested it be set at 150 G to protect against concussive head injury. Subsequent acquisitions of the SPH-4 helmet imposed a 300 G peak acceleration limit. Further impact protection improvements to the SPH-4 helmet could not be made without significant redesign (enlargement) of the helmet shell.

The current Army aircrew helmet (HGU-56/P Aircrew Integrated Helmet System) was developed against performance requirements to limit blunt impact head form peak accelerations to 175 G to the headband region and 150 G to the crown and earcup regions. It is reasonable to assume that given the same impact velocity and surface conditions, a helmet that limits the acceleration to 150 G is more protective than the helmet that limits the acceleration to 300 G.

Since Army combat helmets do not have a historical basis for blunt impact protection requirements, appropriate criteria must be established and should be based on threat and physiological response. In this determination, consideration should be given to: 1) the type of blunt impacts expected, 2) the type of injury to be prevented, and 3) the capability of the available helmet. The motorcycle helmet standards with peak acceleration limits of 300 G are intended to prevent serious head injury. However, protection from concussive head injury would be more appropriate in Army operational environments as emergency medical treatment is not always readily available. For example, an aircrew protective helmet that prevents concussion during a potentially survivable aircraft mishap permits an aviator to self-extract from wreckage and radio for assistance. A similar argument could be made for infantry helmets. By following Slobodnik's (1980) recommendation for aircrew helmets, the blunt impact performance goal for infantry helmets should also be a peak acceleration limit of 150 G. However, this requirement may be difficult to achieve due to the limited standoff distance available between the scalp and inside surface of the PASGT helmet shell. Ballistic protection requirements often drive the design of combat helmets, and blunt impact protection has previously received minimal design consideration.

For the purpose of evaluation, two blunt impact pass-fail criteria were used. First, the mean (average) peak acceleration limit was 150 G, considering all impact sites and all environmental conditions. Second, the maximum individual peak impact acceleration limit was 300 G for all impact sites and environmental conditions. Thus, unacceptable helmet impact acceleration responses were those that produced mean peak accelerations exceeding 150 G, or individual tests with peak accelerations exceeding a maximum value of 300 G.

Combat helmet test impact velocity

The lack of blunt impact performance requirements for the combat helmet also introduces the decision to select the desired impact velocity. The 10.0 fps impact velocity was chosen since preliminary testing suggested the new ACH helmet design would meet the 150 G mean and 300 G peak headform acceleration limits. However, if improvements to combat helmet blunt impact protection are sought, then this impact velocity should be raised to reflect more realistic operational blunt impact velocity threats and environments.

For reference considerations, the required blunt impact test velocities required by various helmet standards are provided in Table 3. In comparison to the established standards, the selected test velocities (10.0 and 14.14 fps) for the combat helmet are low.

Table 3.
Protective helmet blunt impact test velocity requirements.

Reference standard	Impact velocity (fps)	Impact region	Impacts per site	Impact anvil
FMVSS 571.218	17.1	Headband & above	2	Hemispherical
	19.7	Headband & above	2	Flat
ANSI-Z90.1	22.6	Headband & above	1 st	Flat, hemisphere, ¼ inch edge
	19.7	Headband & above	2 nd	Flat and hemisphere
Snell 2000	25.2	Headband & above	1 st	Flat, hemisphere, ¼ inch edge
	21.5	Headband & above	2 nd	Flat and hemisphere
US Army aviator helmet (HGU-56/P)	16.0	Crown	1	Flat
	19.7	Headband & earcup	1	Flat

To establish target goals for blunt impact protection, consideration should be given to the airborne environment. Army paratrooper operations are conducted with either the T-10C or MC1-1B/C parachutes. These parachutes are static-line deployed upon aircraft exit. Typical rates of descent vary depending on the parachute type, suspended load, and relative air density. Descent rates range from 14 fps to 23 fps for the MC1-1C and T-10C parachutes, respectively. The suspended load is the combined weight of the parachute jumper with combat gear and is not to exceed 500 pounds. The maximum load-bearing capacity to achieve a 22 fps or less descent rate is 360 pounds. During the parachutist descent phase, the paratrooper lowers his combat field pack (if it exceeds 35 pounds) with a 15-foot nylon lowering line. Thus, the field pack makes initial ground contact and reduces the suspended weight carried by the parachute during the last 15 feet of descent. This brief weight reduction allows the parachutist descent rate to slow prior to ground contact and the subsequent PLF.

To reduce the possibility of injury during ground contact, the paratrooper is taught to absorb the impact by executing the PLF technique into the direction of wind drift. The PLF technique is a body-rolling technique, allowing the body to roll from the balls of feet to the calf, thigh, buttock, and then the back. If performed properly, this rolling technique reduces the closure velocity between the helmet and ground. Also, the parachutist is taught to tuck his chin against his chest and keep the neck tense during the PLF. This head tucking procedure is intended to prevent head/helmet contact with the ground during a properly executed PLF. The reduction in head closure velocity due to the PLF has not been determined. In a worst case scenario, a parachutist who is incapacitated or otherwise fails to execute the PLF, could potentially experience a head strike at the same velocity as the parachute descent rate.

With a descent velocity range between 14 and 22 fps, reasonable considerations for helmet impact velocities are 10.0, 14.14, 17.32, and 20.0 fps. The 10 fps could represent a parachutist

descending at the lowest descent rate (14 fps) and executing a poor PLF. Likewise, the 14.14 fps velocity could represent an 18 fps parachutist descent. The impact energy ($KE = \frac{1}{2} mv^2$) produced by the 11-pound test head form at these velocities are 17, 34, 51, and 68 foot-pounds, respectively (each energy level is a multiple of 17). More research is needed to determine actual head impact velocities experienced during PLF.

Statistical analysis

A statistical software package, Number Cruncher Statistical System (NCSS), was used to perform analyses of variance (ANOVA) on the various groups of data. The probability of a Type I error was set at 0.05. When an ANOVA resulted in a statistically significant difference, one- and two-factor Tukey-Kramer post-hoc analyses were performed to determine the statistical significance of individual differences within a group. Correlation analyses were performed using the correlation procedure found under the data analysis tool of Microsoft Excel (Excel 2003). For some comparisons, specifically those for first versus second impact tests and impact site symmetry, a t-test was performed using the appropriate conditions of equal or unequal variance ($\alpha = .05$). Descriptive statistics for mean, standard deviation, maximum data value and number of observations was determined using functions contained in Microsoft Excel.

Results and analysis

Test results for 10 fps impact velocity

The results for the 10 fps impacts were analyzed by environmental temperature, impact site and helmet type. Considering all 10 fps data, significant differences were found by environmental temperature, impact site, and helmet type whether the factors were taken individually or in combination. The individual helmet results and then the direct helmet comparisons are presented below.

For each helmet type, the individual acceleration response data points are plotted in Figure 8, grouped by impact site and with the different environmental conditioning temperatures indicated by different symbol shape. Inspection of this figure reveals two observations. First, the ACH appears to perform more poorly in the hot environment than in cold or ambient conditions. This is present in the data for the back and the left and right nape impact sites. However, this trend does not reveal itself in the paratrooper or infantry PASGT helmet data plots. This suggests the ACH helmet impact performance has a temperature dependency. These three impact sites also show more scatter than the other impact sites for the ACH helmet. Second, in comparing the PASGT paratrooper and infantry data plots of Figure 8, higher readings and greater data scatter were received at the back and the two nape impact sites (left and right) for the infantry PASGT helmet. This suggests the addition of the nape pad to the paratrooper configuration has a positive effect in managing the impact energy at these locations. The effect of the PIL addition is not clearly distinguishable from these data plots.

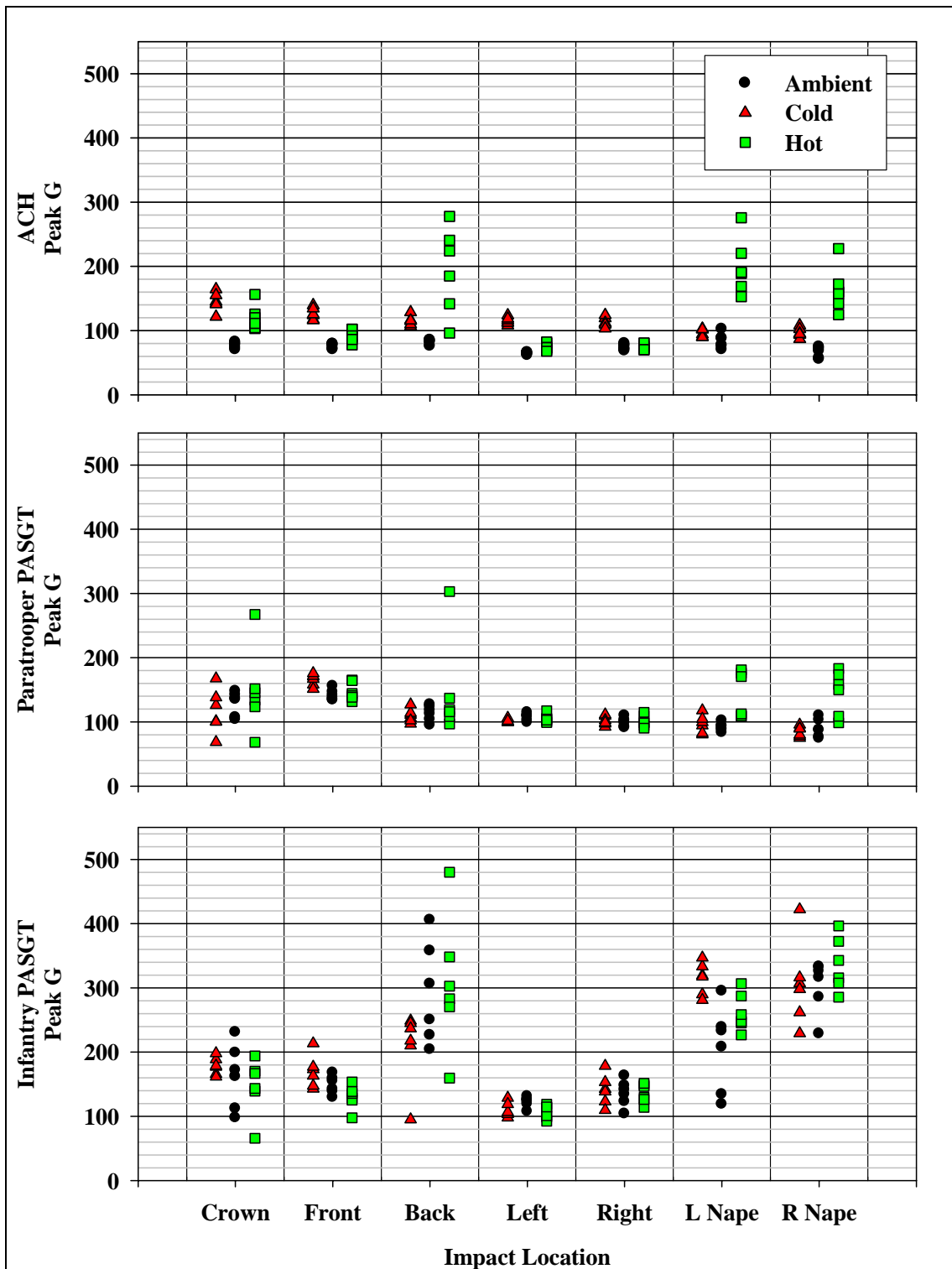


Figure 8. Impact acceleration data (initial and subsequent impacts) by helmet type, impact site and temperature, tested at 10 fps.

Individual helmet analysis

ACH

The means of the peak impact acceleration results for the ACH at a 10 fps impact velocity are plotted in Figure 9 by impact site and environmental temperature. The mean response by temperature is shown in Table 4. None of the mean peak acceleration data for any temperature condition exceeded 150 G. The mean results across impact sites are shown in Table 5. None of the mean values, by impact site, exceeded 150 G. No individual ACH impact acceleration response exceeded the 300 G limit.

Significant differences were found by impact site, environment and by the combined factors of impact site and temperature. In this series across all impact sites, all test temperature results differed from each other. Across all test temperatures, several sites differed significantly from each other. Notably, while the left and right sites did not differ from each other, they did significantly differ from the other sites. Considering both impact site and test temperature, the results for the hot-back, hot-left nape and hot-right nape were significantly different.

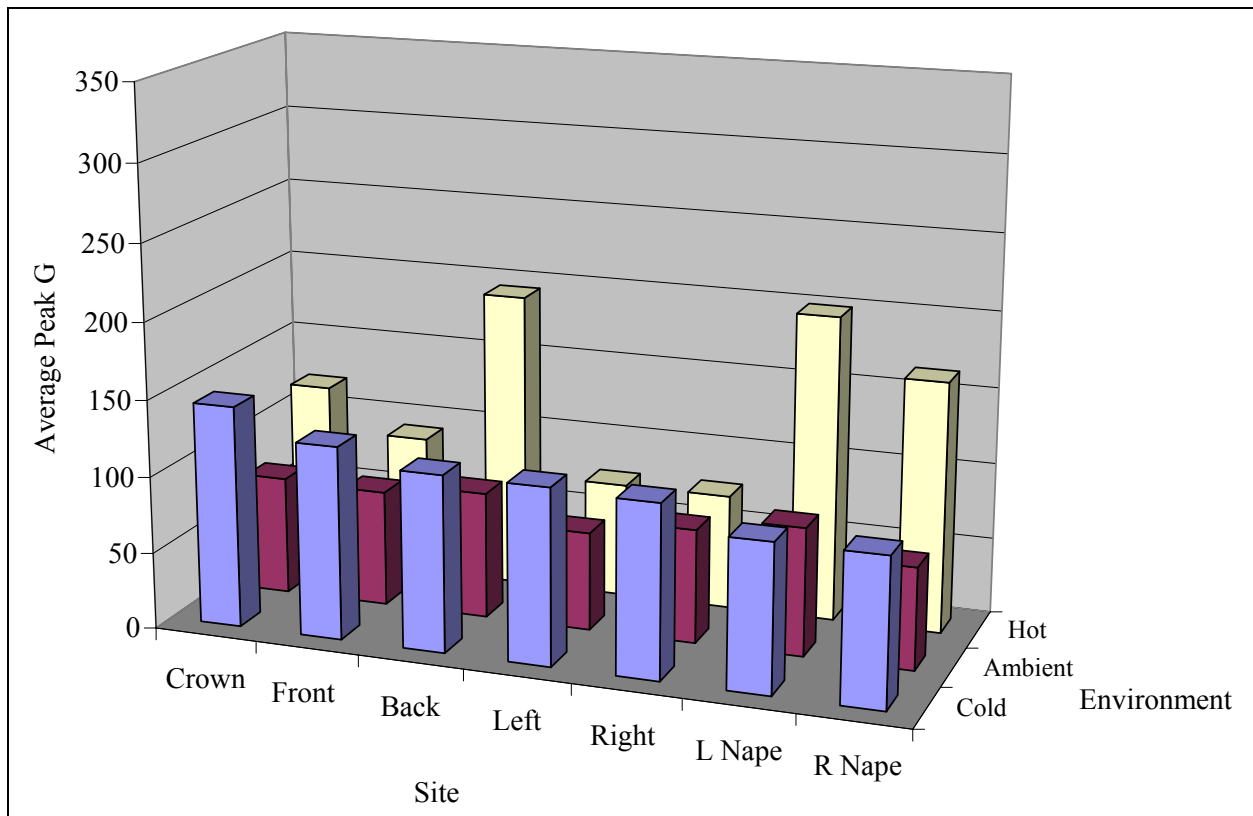


Figure 9. Mean impact accelerations (G) of the ACH tested at 10 fps, by impact site and environment temperature.

Table 4.
ACH impact summary statistics, by temperature, tested at 10 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	75	116	131
Standard Deviation (G)	9	18	60
Maximum (G)	102	164	278
Observations (n)	42	42	42

Table 5.
ACH impact summary statistics, by impact site, tested at 10 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	114	98	131	85	87	127	109
Standard Deviation (G)	32	23	61	23	20	59	46
Maximum (G)	164	140	278	124	124	276	228
Observations (n)	18	18	18	18	18	18	18

Paratrooper PASGT

The means of the peak impact acceleration results for the Paratrooper PASGT at a 10 fps impact velocity are plotted in Figure 10 by impact site and environmental temperature. The mean peak acceleration response by temperature is shown in Table 6. None of the means exceeded 150 G. In the hot environment, the maximum peak acceleration exceeded 300 G. For the mean peak acceleration by impact site (Table 7) only the mean peak acceleration for the front impact site (152 G) exceeded the 150 G mean threshold, while only the back impact site (303 G) produced a peak acceleration value in excess of 300 G.

Significant differences were found by impact site, by temperature and by impact site and test temperature. Considering the data by impact site alone across temperature, the front site differed from all other sites. Considering the data by environmental temperature across impact sites, the hot temperature differed from the ambient and cold conditions. For the combined factors of temperature and impact site, the cold-front and the cold-right nape were notably different from the other combined factors as high and low values, respectively.

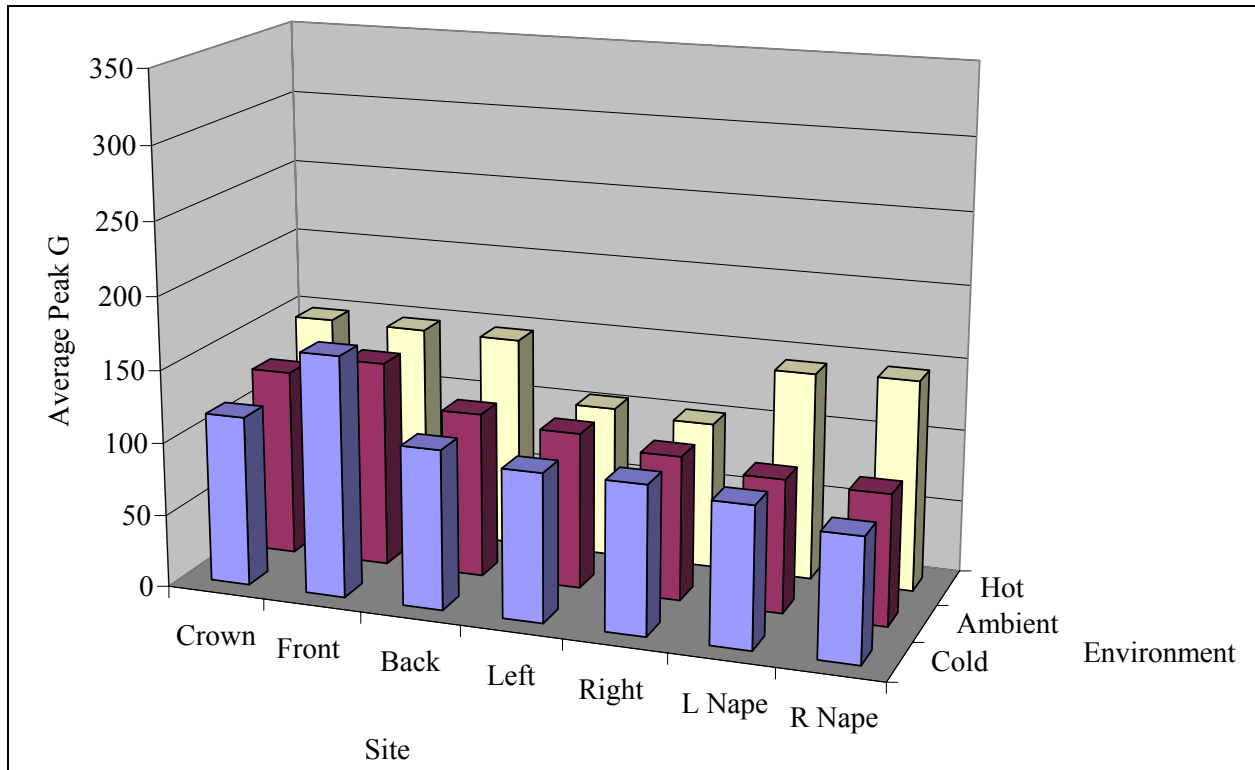


Figure 10. Mean impact accelerations (G) of the Paratrooper PASGT tested at 10 fps, by impact site and environment temperature.

Table 6.

Paratrooper PASGT impact summary statistics, by temperature, tested at 10 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	110	111	134
Standard Deviation (G)	21	29	45
Maximum (G)	156	176	303
Observations (n)	42	42	42

Table 7.

Paratrooper PASGT impact summary statistics, by impact site, tested at 10 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	131	152	123	105	101	110	107
Standard Deviation (G)	44	15	46	5	8	32	35
Maximum (G)	267	176	303	117	115	181	183
Observations (n)	18	18	18	18	18	18	18

Infantry PASGT

The mean results for the Infantry PASGT impact tests at a 10 fps impact velocity are plotted in Figure 11 by impact site and environmental temperature. The mean peak accelerations by temperature (Table 8) all exceeded 150 G. The maximum peak accelerations for all environmental conditions exceeded 300 G. However, in Table 9 for the mean by impact site, the back, crown, left nape and right nape mean values exceeded 150 G, while the back, left nape and right nape maximum values exceeded 300 G.

Significant differences were found by impact site and by impact site and test temperature but not by temperature alone. Significant differences by impact site were found across environmental temperature. The back, left nape and right nape were most notably different as high values. Considering the combined factors of impact site and temperature, several significant differences were found, but these differences were influenced by the large differences by impact site alone.

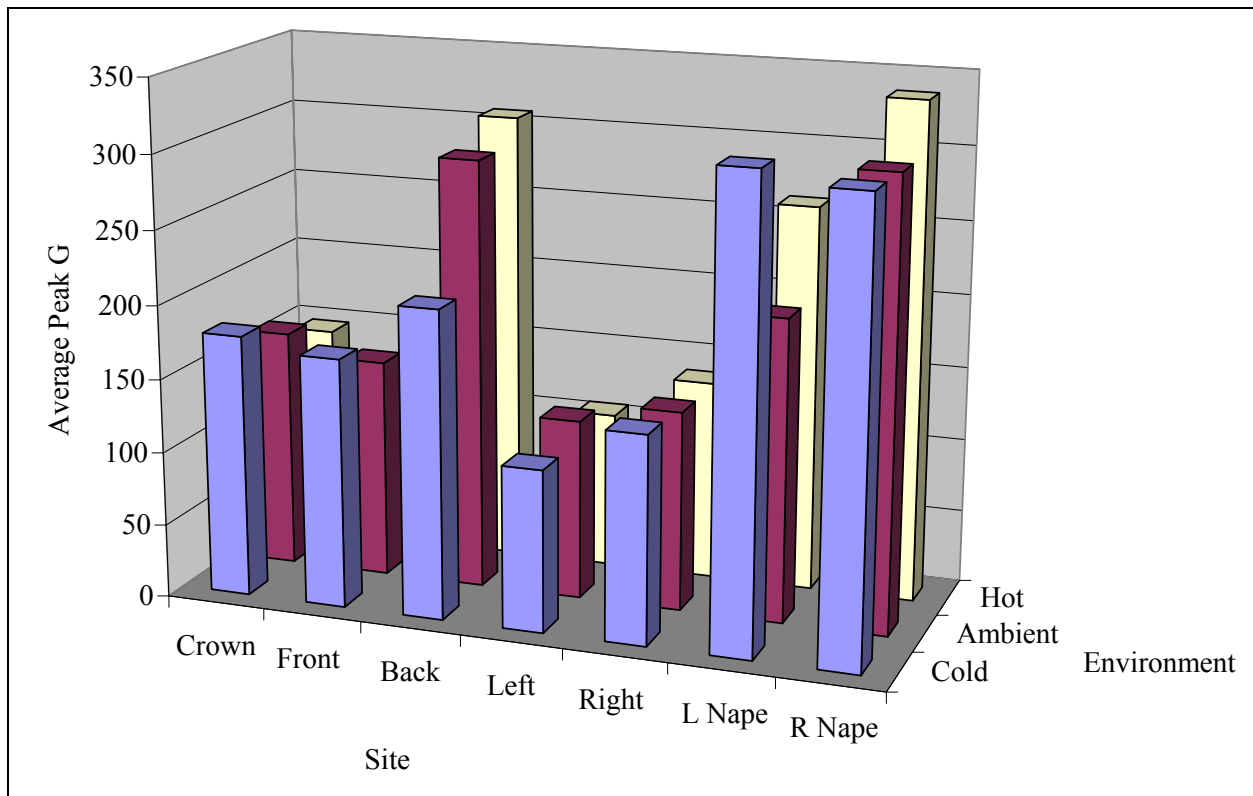


Figure 11. Mean impact accelerations (G) of the Infantry PASGT tested at 10 fps, by impact site and environment temperature.

Table 8.
Infantry PASGT impact summary statistics, by temperature, tested at 10 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	196	204	204
Standard Deviation (G)	82	82	100
Maximum (G)	406	422	480
Observations (n)	42	42	42

Table 9.
Infantry PASGT impact summary statistics, by impact site, tested at 10 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	162	149	269	113	138	261	315
Standard Deviation (G)	40	25	90	12	19	62	50
Maximum (G)	231	214	480	131	179	347	422
Observations (n)	18	18	18	18	18	18	18

Direct helmet comparisons

Overall comparisons

The peak acceleration grand means and standard deviations for each helmet tested are shown in Table 10. Only the Infantry PASGT mean value was above 150 G. All grand means were significantly different from each other with the Infantry PASGT being 80 to 90 G higher than the Paratrooper PASGT and ACH, respectively. The maximum peak acceleration values for each helmet tested at 10 fps also are shown in Table 10. Only the ACH helmet provided peak accelerations below 300 G, the other helmets exhibited at least one result in excess of that limit.

Table 10.
Peak acceleration summary statistics for all helmets tested at 10 fps.

Statistic	ACH	Paratrooper PASGT	Infantry PASGT
Mean (G)	107	118	201
Standard Deviation (G)	43	34	88
Maximum (G)	278	303	480
Observations (n)	126	126	126

Analysis by environmental temperature

The 10 fps impact data were analyzed at each environmental condition by helmet (Table 11), to determine the influence of temperature on helmet impact response. The ACH, Paratrooper PASGT and Infantry PASGT differed significantly with respect to temperature effects, with the Infantry PASGT measuring consistently at least 75 to 100 G higher than the others. While the ambient temperature ACH and Paratrooper PASGT results differed, the cold and hot results did not differ significantly.

Table 11.
Mean peak accelerations (G) by helmet and temperature tested at 10 fps.

Environmental Condition	ACH	Paratrooper PASGT	Infantry PASGT
Ambient	75	110	196
Cold	116	111	204
Hot	131	134	204

Analysis by impact site

The impact data at 10 fps was analyzed at each impact site by helmet (Table 12), to determine the influence of impact site on helmet impact response. Significant differences were found by impact site for all helmets. Most notably, the Infantry PASGT results for the back, left nape and right nape were at least 150 to 225 G greater than the results for the Paratrooper PASGT and ACH. However, the ACH and Paratrooper PASGT results were still significantly different after removing the Infantry PASGT data from consideration.

Table 12.
Mean peak accelerations (G) by helmet and impact site tested at 10 fps.

Impact Site	ACH	Paratrooper PASGT	Infantry PASGT
Crown	114	131	162
Front	98	152	149
Back	131	123	269
Left side	85	105	113
Right side	87	101	138
Left nape	127	110	261
Right nape	109	107	315

Initial versus subsequent impacts

The peak accelerations at the 10 fps impact velocity grouped by helmet, impact site and environmental temperature were plotted against each other to compare the impact attenuation between the initial and subsequent impacts. Figure 12 shows the relationship of each helmet and environmental temperature grouping where the individual plotted points represent the various impact sites. Also plotted on the graph is the “slope of one,” straight line relationship to indicate the degree of divergence from equivalence. The ACH data points fall near the unity line up to 120 G, at which point the second impacts generally produced a higher response than the initial impact. The cases where the ACH data fall away from the unity line are hot environments and at the nape and back impact sites. This suggests the ACH fitting pads may be sensitive to the hot environment, or have an impact site dependency. The Paratrooper and Infantry PASGT data both show divergence from the unity line, with the Paratrooper PASGT data showing a tight data cluster around the 100 G level and the Infantry PASGT a general scatter. A correlation analysis of the first versus second impact response was performed by helmet. All correlations were statistically significant with r values of 0.95, 0.54 and 0.85 (r^2 values of 0.90, 0.29, and 0.72, respectively) for the ACH, Paratrooper PASGT, and Infantry PASGT helmets, respectively.

Impact response symmetry

Since the helmet systems tested were basically symmetric about the sagittal plane, one would expect similar impact response at matching side to side impact sites. A lack of similarity would indicate possible head form, helmet fitting or helmet design problems and require testing to be conducted at each impact site. The helmet systems were analyzed with respect to right versus left side and right nape versus left nape impact results to determine if statistically significant differences existed between those sites at the 10 fps impact velocity. The paired data consisting of both impacts across all environmental temperatures were subjected to a two-tailed t-test assuming equal and unequal variance. No statistically significant differences were found for right versus left impact sites or for right nape versus left nape impact sites for the ACH or the Paratrooper PASGT helmets. For the Infantry PASGT, the right versus left side and the right nape versus left nape comparisons were significantly different.

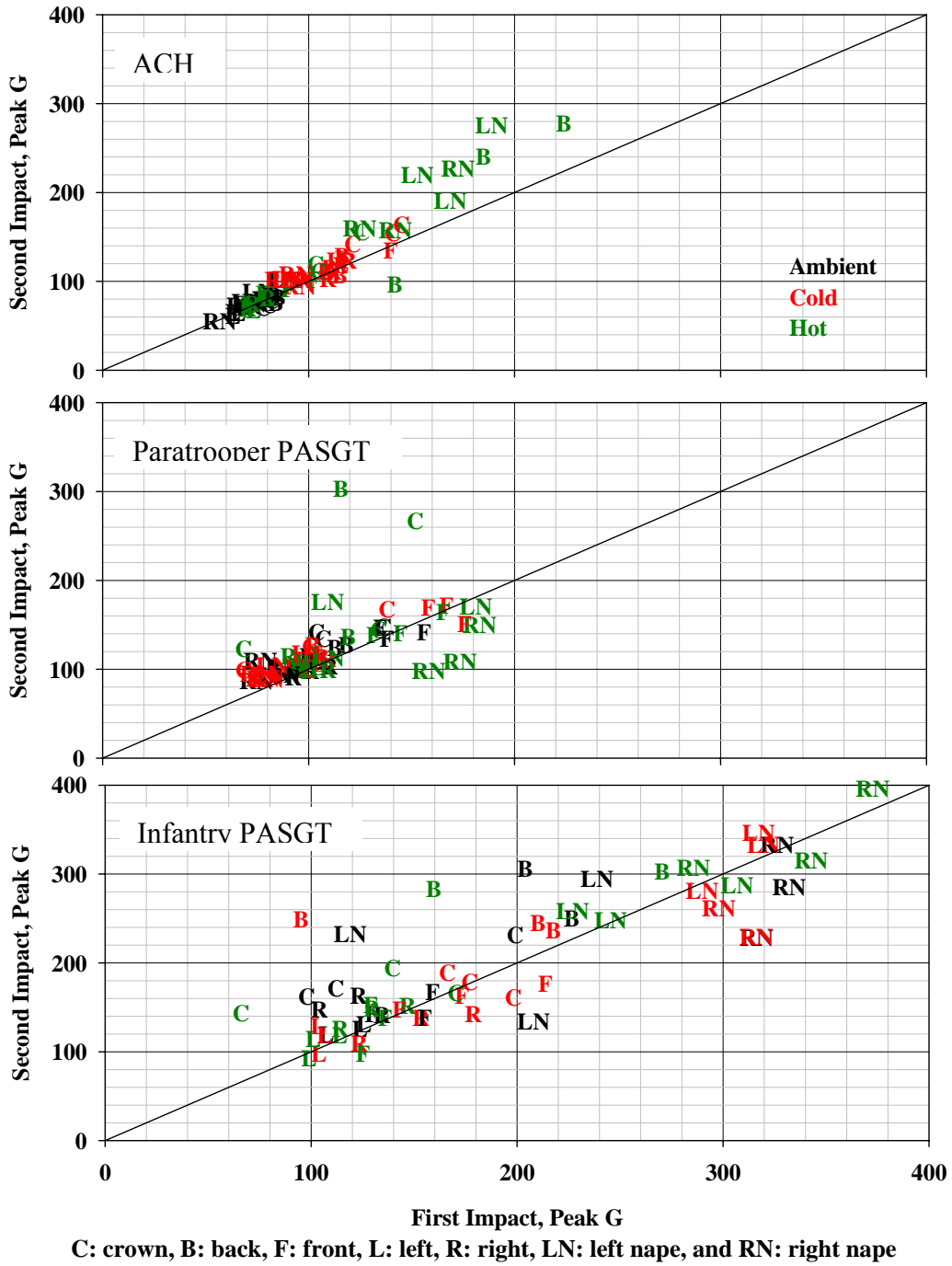


Figure 12. Initial versus subsequent impact response of all helmets tested at 10 fps.

Test results for 14.14 fps impact velocity

The blunt impact test results (peak acceleration) for the 14.14 fps impacts were analyzed by environmental temperature, impact site and helmet type. The individual data points for all impacts (first and second) are shown in Figure 13, grouped by helmet type and impact site with environmental temperature indicated by symbology.

Considering all 14.14 fps data, significant differences were found by environmental temperature, impact site and helmet, whether the factors were taken individually or in combination. The individual helmet results and then the direct helmet comparisons are presented below.

Individual helmet analysis

ACH

The mean results for the ACH impact tests at a 14.14 fps impact velocity are plotted in Figure 14 by impact site and environmental temperature. In the mean peak accelerations (Tables 13 and 14), all mean values exceeded 150 G. Only the cold environment condition did not exceed the 300 G peak acceleration value.

Considering the combined impact results, significant differences were found by impact site, test temperature, and the combined factors of impact site and test temperature. For impact site alone, the mean acceleration values for the right nape and left nape, as well as the right and left impact sites, stand out as high and low values, respectively. By test temperature alone, all temperatures were significantly different from each other, with the hot temperature results being 200 to 250 G higher than the cold and ambient results, respectively. Considering the combined factors of test temperature and impact site, a number of significant differences were found, the most notable being the hot-right nape, hot-left nape and hot-back, with mean values exceeding 500 G.

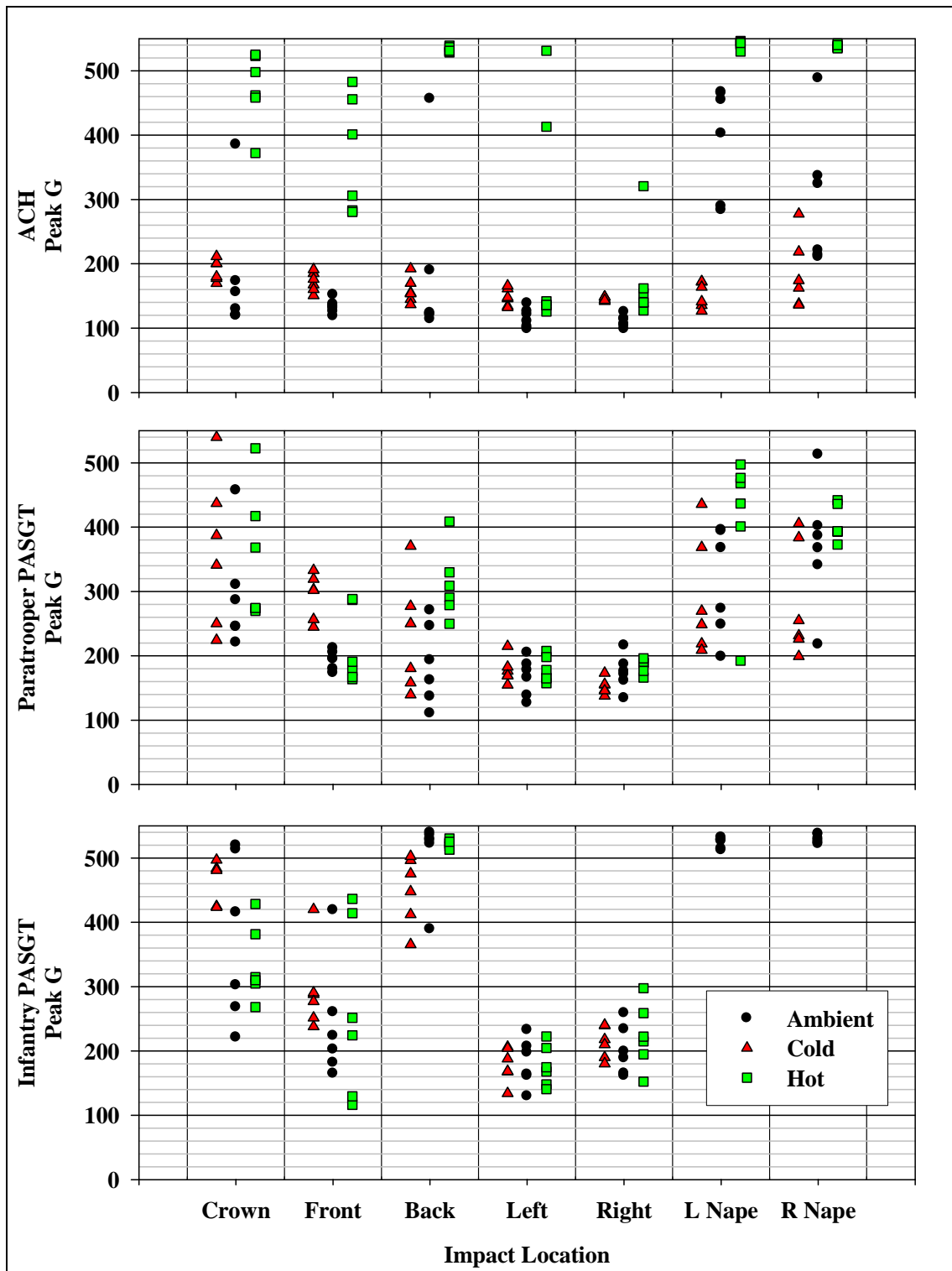


Figure 13. Impact acceleration data (initial and subsequent impacts) by helmet type, impact site and temperature, tested at 14.14 fps.

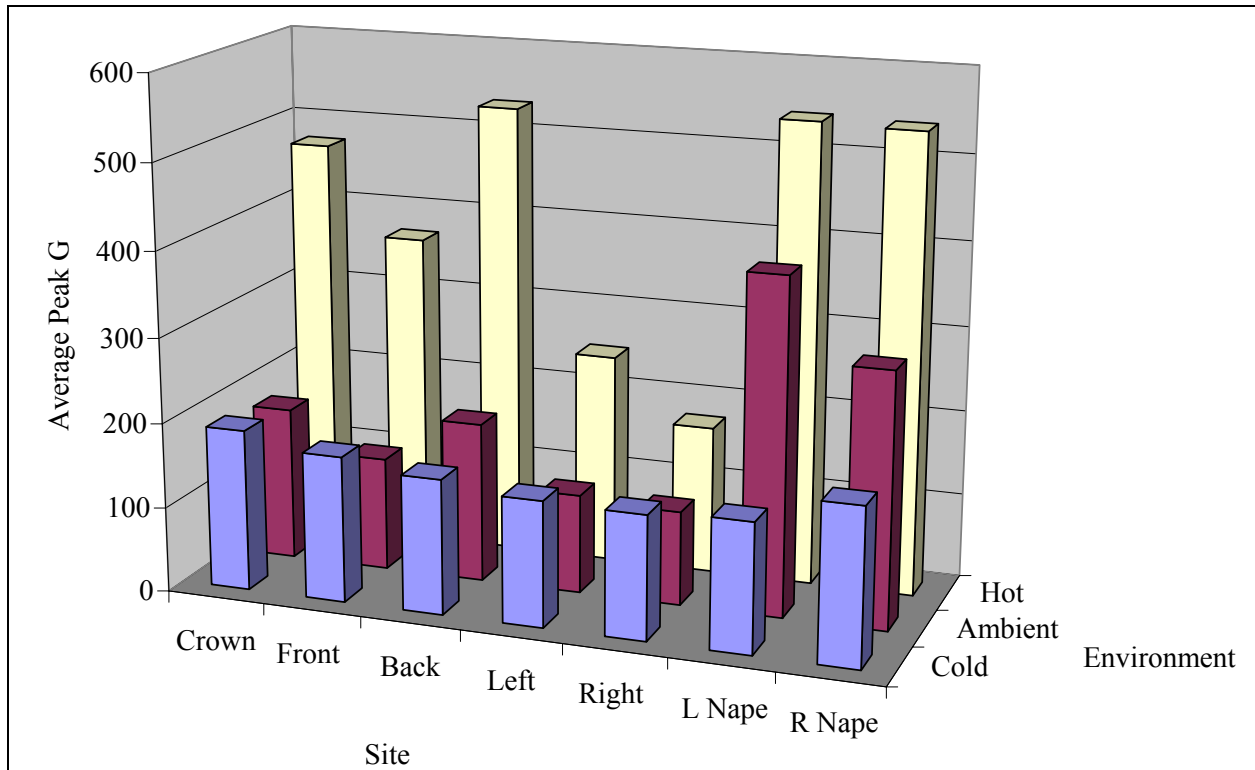


Figure 14. Mean impact accelerations (G) of the ACH tested at 14.14 fps, by impact site and environment temperature.

Table 13.

ACH impact summary statistics, by temperature, tested at 14.14 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	203	164	411
Standard Deviation (G)	126	29	161
Maximum (G)	489	278	546
Observations (n)	42	42	42

Table 14.

ACH impact summary statistics, by impact site, tested at 14.14 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	281	224	293	170	144	362	341
Standard Deviation (G)	154	117	190	113	48	172	165
Maximum (G)	525	483	539	531	321	546	543
Observations (n)	18	18	18	18	18	18	18

Paratrooper PASGT

The mean results for the Paratrooper PASGT at a 14.14 fps impact velocity are plotted in Figure 15 by impact site and environmental temperature. All of the mean values exceeded 150 G and the maximum peak accelerations in all environmental temperatures exceeded 300 G. These results are shown in Table 15. By impact site, all the means exceeded 150 G (Table 16). Except for the left and right impact sites, all other impact sites experienced maximum acceleration values in excess of the 300 G threshold.

Considering the combined impact results, significant differences were found by impact site, by test temperature and the interaction of impact site and test temperature. For impact site alone, the crown, right nape and left nape, as well as the right and left mean acceleration values, stand out as high and low values, respectively. By test temperature alone, the hot temperature results were significantly different from the ambient and cold temperature results. The hot temperature results were 40 to 50 G higher than the cold and ambient results, respectively. Considering the combined factors of test temperature and impact site, a number of significant differences were found.

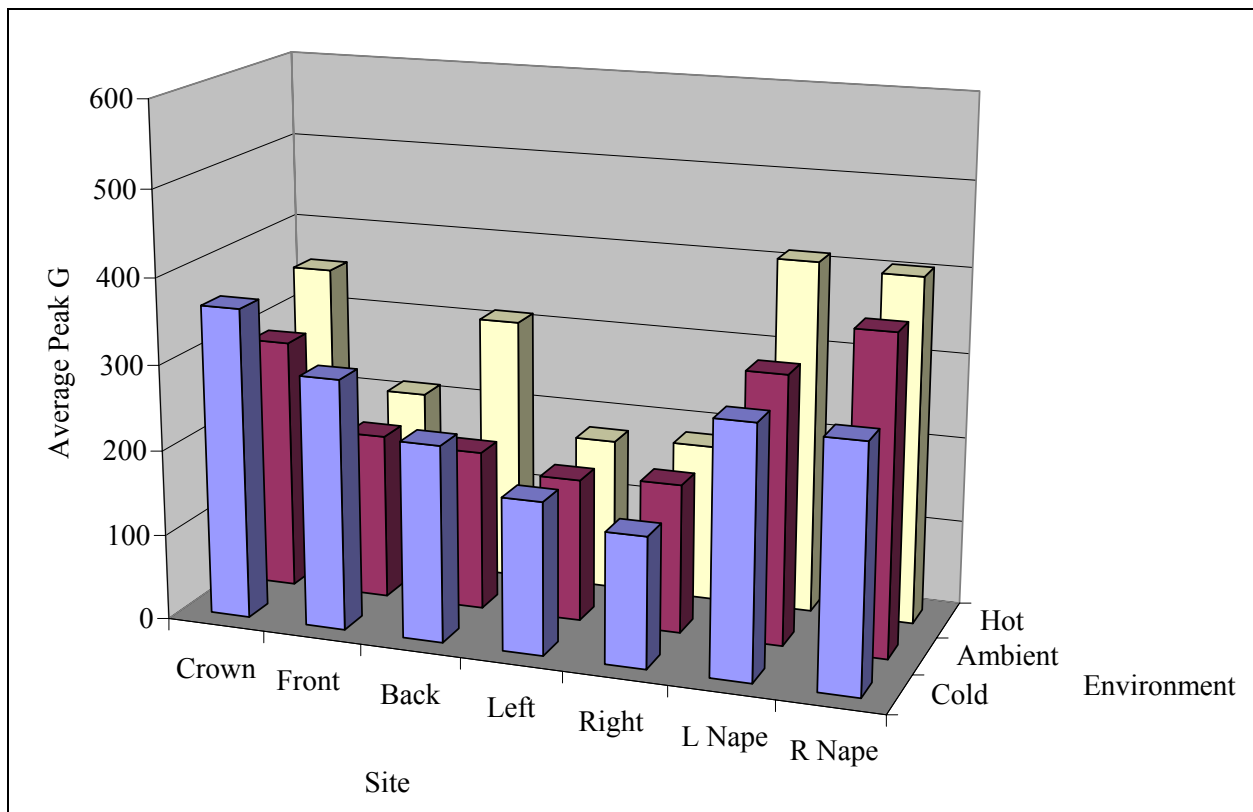


Figure 15. Mean impact accelerations (G) of the Paratrooper PASGT tested at 14.14 fps, by impact site and environment temperature.

Table 15.

Paratrooper PASGT impact summary statistics, by temperature, tested at 14.14 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	243	256	294
Standard Deviation (G)	97	98	114
Maximum (G)	513	540	523
Observations (n)	42	42	42

Table 16.

Paratrooper PASGT impact summary statistics, by impact site, tested at 14.14 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	337	233	242	175	170	339	353
Standard Deviation (G)	102	58	84	23	22	106	89
Maximum (G)	540	333	409	215	216	498	513
Observations (n)	18	18	18	18	18	18	18

Infantry PASGT

The mean test results for the Infantry PASGT at a 14.14 fps impact velocity are plotted in Figure 16 by impact site and environmental temperature. For all temperature conditions, the mean peak accelerations exceeded 150 G and the maximum peak accelerations exceeded 300 G (Table 17). By impact site (Table 18), the mean accelerations exceeded 150 G in all cases, while the maximum value by impact site exceeded 300 G for all impact sites except the left and right sides.

Considering the combined impact results, significant differences were found by impact site but not by test temperature or the combined factors of temperature and impact site. The front impact site demonstrated an impact response between that of the other sites. The left and right sides demonstrated the lower response, while the crown and back impact sites produced a higher impact response.

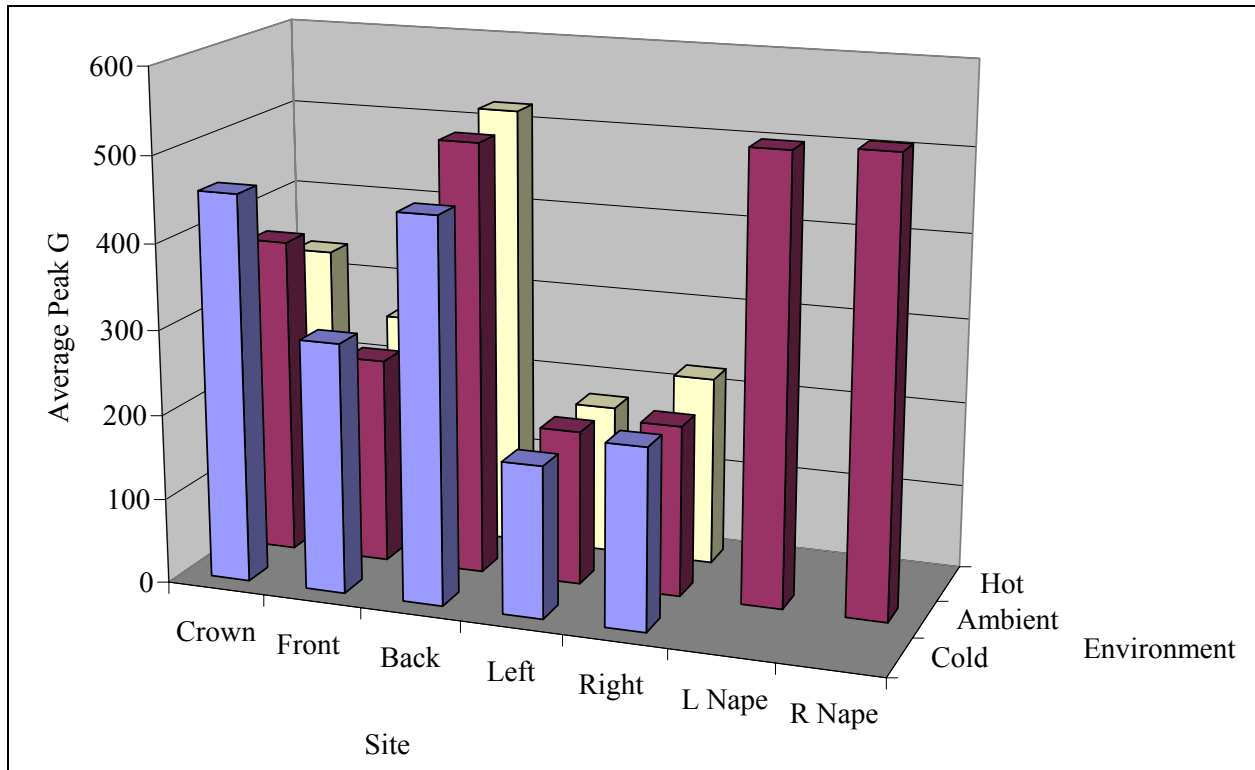


Figure 16. Mean impact accelerations (G) of the Infantry PASGT tested at 14.14 fps, by impact site and environment temperature.

Table 17.

Infantry PASGT impact summary statistics, by temperature, tested at 14.14 fps.

Statistic	Ambient	Cold	Hot
Mean (G)	366	318	304
Standard Deviation (G)	160	125	140
Maximum (G)	540	503	530
Observations (n)	42	30	30

Table 18.

Infantry PASGT impact summary statistics, by impact site, tested at 14.14 fps.

Statistic	Crown	Front	Back	Left	Right	Left Nape	Right Nape
Mean (G)	388	266	493	179	213	524	530
Standard Deviation (G)	94	99	53	31	38	8	7
Maximum (G)	520	436	540	233	298	532	538
Observations (n)	18	18	18	18	18	6	6

Direct helmet comparisons

Overall comparisons

The peak acceleration grand means and standard deviations for each helmet for the front, crown, back, right side and left side impact sites are shown in Table 19. The right nape and left nape sites were excluded from Table 19 due to incomplete data for all conditions. All the mean peak values exceeded 150 G and all maximum peak values exceeded 300 G. The grand means for the ACH and Paratrooper PASGT were not significantly different from each other, while both helmets were significantly different for the Infantry PASGT. The Infantry PASGT was 70 to 80 G higher than the Paratrooper PASGT and ACH, respectively.

Table 19.

Peak acceleration summary statistics for all helmets tested at 14.14 fps.

Statistic	ACH	Paratrooper PASGT	Infantry PASGT
Mean (G)	259	264	333
Standard Deviation (G)	160	105	146
Maximum (G)	546	540	540
Observations (n)	90	90	90

Note: These statistics were calculated based on the results from the front, crown, back, right and left side impact sites. The right and left nape impacts sites were excluded from the calculations since these test sites were not evaluated in the hot and cold environmental conditions.

Analysis by environmental temperature

The combined first and second impact data at 14.14 fps were analyzed at each environmental condition across impact sites by helmet (Table 20), to determine the influence of temperature on helmet impact response. The ACH, Paratrooper PASGT and Infantry PASGT differed significantly with respect to temperature effects. The Infantry PASGT demonstrated the highest mean impact response acceleration, followed by the Paratrooper PASGT and lastly the ACH.

Table 20.

Mean peak accelerations (G), by helmet and temperature tested at 14.14 fps.

Environmental Condition	ACH	Paratrooper PASGT	Infantry PASGT
Ambient	203	243	366
Cold	164	256	318
Hot	411	294	304

Analysis by impact site

The impact data at 14.14 fps were analyzed at each impact site by helmet (Table 21) to determine the influence of impact site on helmet impact response. The left nape and right nape were not included in the comparison across all helmets since those conditions were dropped in the Infantry PASGT tests due to acceleration values reaching the measurement limits. Significant differences were found by impact site for all helmets. The left, right and front impact site results were comparable across helmets, but the crown impact site demonstrated increasing impact acceleration values from the ACH to the Paratrooper PASGT, with the Infantry PASGT producing the highest results. The back impact site for the Infantry helmet was the most notably different at 493 G, which was 200 G higher than the next highest value.

Table 21.

Mean peak accelerations (G), by helmet and impact site tested at 14.14 fps.

Impact Site	ACH	Paratrooper PASGT	Infantry PASGT
Crown	281	337	388
Front	224	233	266
Back	293	242	493
Left side	170	175	179
Right side	144	170	213
Left nape	362	339	524*
Right nape	341	353	530*

*Left nape and right nape impact tests for the Infantry PASGT were conducted in the ambient environmental condition only. Due to the high acceleration results obtained at the ambient condition, the hot and cold conditions were not tested.

Initial versus subsequent impacts

The peak accelerations at the 14.14 fps impact velocity grouped by helmet, impact site, and environmental temperature were plotted against each other to compare the impact attenuation between the initial and subsequent impacts. Figure 17 shows the relationship of each helmet and environmental temperature grouping where the individual plotted points represent the various impact sites. Also plotted on the graph is the “slope of one,” straight line relationship, to indicate the degree of divergence from equivalence. Greater divergence from equivalence was seen for all three helmet types at 14.14 fps than at 10 fps. A correlation analysis of the first versus second impact response was performed by helmet. All correlations were statistically significant with r values of 0.84, 0.73 and 0.88 (r^2 values of 0.71, 0.53, and 0.77 respectively) for the ACH, Paratrooper PASGT and Infantry PASGT helmets, respectively. For the ACH, while the cold and hot impact data seemed to be clustered about specific regions on the graph in Figure 17, the ambient back and nape impact data were widely scattered above the line. The Paratrooper PASGT data seemed evenly scattered above the unity line regardless of temperature or impact site, except for one hot-left nape data point. The Infantry PASGT was also seen to be widely scattered, except for a concentration of ambient temperature data points at above 500 G which are probably truncated data due to exceeding the measurement system’s capability.

Impact response symmetry

The 14.14 fps impact velocity was not assessed for impact response symmetry because some of the measured impact accelerations were at the limit of the measurement system, and the actual results were possibly higher than indicated.

Discussion

Significant impact acceleration differences have been demonstrated within and between helmet systems by environmental temperature and impact site for the two impact test velocities. Mean and maximum value thresholds were used for assessment and comparison purposes. Considering the data by environmental temperature or impact site, the ACH did not exceed the mean or maximum value thresholds at 10 fps. The Paratrooper PASGT exceeded the maximum value threshold for the back impact site and the mean value threshold for the front impact site, but no other impact sites or environmental temperature results exceeded either threshold. The Infantry PASGT results by impact site and environmental temperature at 10 fps exceeded the mean, maximum or both threshold values for practically all conditions. At 14.14 fps, the results for all helmets and variable conditions exceeded the mean, maximum or both threshold values. The only helmet that passed all testing at 10 fps was the ACH. The Paratrooper PASGT passed in all but two conditions at 10 fps. Both the ACH and Paratrooper PASGT exhibited multiple failures at the 14.14 fps impact velocity. The Infantry PASGT routinely exceeded the threshold values for both impact velocities.

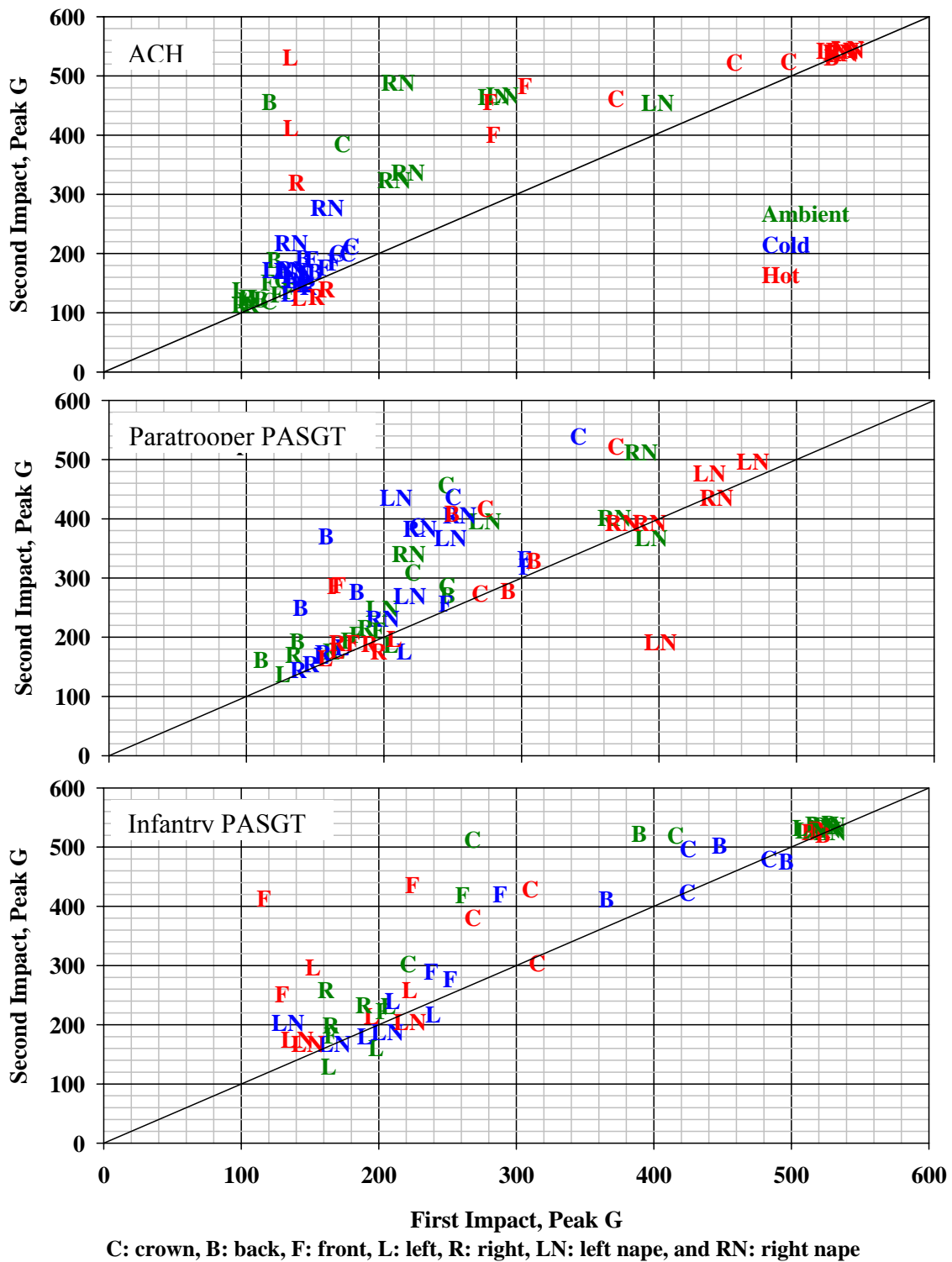


Figure 17. Initial versus subsequent impact response of all helmets tested at 14.14 fps.

Considering only the ACH, interesting impact acceleration response differences were noted by test temperature. The ACH exhibited higher impact accelerations at the hot temperature compared to the cold and ambient temperatures. This response in general is expected given that part of the impact attenuation system consists of a viscoelastic foam material that demonstrates a higher compliance with increased temperatures resulting in decreased energy absorption (Anderson, White, and McLean, 2000, Davies and Mills, 1999). During the hot environment 10 fps tests, the back, right nape and left nape sites, while all below either threshold, exhibited higher impact accelerations compared to the other impact sites. However, these impact site differences were not apparent at the higher impact velocity where all sites were affected by the hot environmental temperature. ACH demonstrated more temperature dependency than the PASGT helmets, while the PASGT helmets tended to demonstrate more site specific dependencies. These response characteristic differences can be attributed to the differences in helmet fitting and impact attenuation materials used in the ACH and PASGT-type helmets. For sequential impacts at 10 fps, an initial impact below the mean impact acceleration threshold value generally was associated with a second impact that was also below that threshold. A notable exception was the hot nape and back conditions for the ACH which were associated with the temperature effect discussed above. Even with the potentially variable placement of the impact pads for the ACH, a symmetric sagittal plane impact response was found at the 10 fps impact velocity.

For the Paratrooper PASGT helmet, the addition of the ½-inch thick rear nape pad tended to force the head form farther forward in the helmet. Consequently, during frontal impacts, there was less stopping distance available between the head form and inside surface of the helmet shell. This may have contributed to the higher readings in this area for this helmet. On both PASGT helmet configurations, the fit of the leather headband and the three overhead adjustment straps were important contributors to the performance in the crown impact. Any loosening or stretching during the time just prior to testing would contribute to poorer results on the crown or any of the subsequent impact sites. The effects of the PIL pads can be distinguished in the PASGT helmet types at the crown and side impact sites. The front, rear, and nape impact sites were potentially affected by the fit alteration of the parachutist nape pad.

While the test conditions of environmental temperature and impact site should give representative indications of operational performance, the performance of the ACH viscoelastic pads were not evaluated after exposure to water. Water is known to significantly decrease the Young's modulus of Confor foam (Davies and Mills, 1999). Although the ACH viscoelastic pads are coated with a water resistant membrane, water contacts in the form of sweat soaking or water immersion are highly likely events. Consideration should be given to a series of tests evaluating any potential effects of water contact duration, temperature and impact site on impact attenuation performance.

Conclusions

The ACH exhibited superior performance at 10 fps impact velocity over the Paratrooper and Infantry PASGT. The ACH did not exceed the mean or maximum threshold criteria at 10 fps impact velocity for any condition. However, the Paratrooper PASGT did fail the mean threshold criteria in only one test condition and the maximum threshold criteria in only one test condition. The addition of the nape and PIL pads in the Paratrooper PASGT improved the impact attenuation when compared to the Infantry PASGT.

None of the helmet systems passed the 14.14 fps impact velocity. If this impact velocity is a design goal, improvements in the helmet's energy attenuation system will be required to provide adequate protection.

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