

A framework for a multi-dimensional composite combat helmet scoring system

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Abstract. The current study presents a framework that scores combat helmet blunt impact performance for different exposure environments. Selecting the best helmet for the operation of interest (e.g. mounted, dismounted, or airborne) depends on several competing factors, such as likelihood of impact locations, impact severities, temperatures, and helmet sizes. These competing factors make it difficult to select the best helmet using the current combat helmet blunt impact evaluation standards that rely on a pass/fail outcome for all test conditions and lack head injury probability estimates. This study hypothesizes that combining field exposure data with biomechanically based head injury risk criteria can result in an improved combat helmet evaluation system. To accomplish this, helmet-mounted acceleration data collected from theatre were analysed to estimate frequency of impacts at different helmet locations, severities, and temperatures. These data were used to inform exposure weights for laboratory blunt impact test results. The risk of injury for seven different combat helmet systems were evaluated using the Head Injury Criterion, calculated from monorail drop tower impacts. The laboratory impact data were combined with the theatre-based exposure weights to estimate the number of injuries that would result from 100 head impacts with the helmet system of interest being worn. For exposure conditions corresponding to a mix of mounted and dismounted exposure conditions, the Enhanced Combat Helmet with Team Wendy pads performed the best (1.45 injuries per 100 impacts) while the Advanced Combat Helmet with custom prototype pads performed the worst (3.39 injuries per 100 impacts). While more helmet sensor and biomechanical research is needed to ensure all types of head injuries are represented in helmet evaluation, this study illustrates how a helmet scoring framework can be an improvement over the current blunt impact evaluation standards.

1. INTRODUCTION

Combat helmets provide protection in a range of operational environments and from a range of operational insults, including blunt and ballistic impacts. Test and evaluation of combat helmets is critical to ensuring they are suitable for head protection. Blunt impact performance is evaluated in a variety of conditions, including various temperatures, impact velocities, and impact locations meant to represent a range of relevant operational exposures.

The current United States (U.S.) Army combat helmet blunt impact standards are based on the drop tower test protocol detailed by McEntire and Whitley [1]. This report focused on the accelerative response of a headform outfitted with an Advanced Combat Helmet (ACH) with a foam pad suspension system and a Personnel Armor System for Ground Troops (PASGT) helmet with a sling suspension system. The approach was based on motorcycle helmet test methods from U.S. Federal Motor Vehicles Safety Standard 218 [2]. For this standard, the U.S. Department of Transportation headform with a modified foam chin was outfitted with either an ACH or PASGT helmet and subjected to either a 3.05 m/s (10.00 ft/s) or 4.31 m/s (14.14 ft/s) impact on a monorail drop tower system. These velocities were chosen based on estimated descent velocities of paratroopers during parachute landing fall, with 3.05 m/s simulating the lower value of the estimated range while executing a poor landing manoeuvre. The 3.05 m/s case is often referred to as the baseline impact energy case, while the 4.31 m/s impacts represented twice the kinetic energy of a baseline impact. McEntire and Whitley found that the ACH with foam pads resulted in more favourable head accelerations compared to the older PASGT helmet and sling suspension system [1]. This assessment was based on the average headform acceleration not exceeding 150 g across all impact conditions. The 150 g acceleration threshold was based on results from Slobodnik's accident reconstruction study with U.S. Army Aviator helmets [3].

Currently, combat helmets must meet a 150 g peak acceleration threshold requirement under all blunt impact test conditions. This includes seven different impact locations (front, crown, left nape, right nape, left side, right side, and rear), three different temperatures (cold, ambient, hot) and four different helmet shell sizes (small, medium, large, x-large). Some helmets are only evaluated at 3.05 m/s while others are tested at 3.05 m/s and 4.31 m/s. While there are benefits to the simplicity of the uniform 150

g pass-fail threshold, there are several drawbacks. First, it can be difficult or impossible to determine if one helmet or suspension system is more protective than another system. One system will often perform better than another system for some test conditions, but worse at other test conditions. With a simple pass-fail criterion, it is difficult to understand if one system is more protective than another if both meet the 150 g criteria for all conditions or if both fail the 150 g criteria for at least one test condition. Secondly, the pass-fail threshold does not accurately reflect the relative risk of injury, which is better represented by a sigmoid shaped curve rather than a step function [4][5]. Additionally, the step function does not incentivize helmet systems to reduce peak accelerations even lower than 150 g and does not penalize helmet systems more so for having even higher peak accelerations. Thirdly, the 150 g requirement uniformly applied to all test conditions does not reflect operational conditions and does not allow for a tailored assessment for different mission profiles. Operationally, there are certain impact conditions (i.e. temperatures, impact locations, impact velocities) that are more prevalent than others, and thus a helmet system that provides better protection for the more common impact conditions would likely result in overall lower prevalence of injuries compared to a different helmet system, even if both helmet systems meet the 150 g criteria for all impact conditions. The uniform pass-fail criterion also makes it difficult to determine the most protective helmet system for different end-users or missions that have different exposure profiles (e.g. arctic paratrooper versus dismounted soldier in the tropics).

From a helmet and suspension system development perspective, the pass/fail requirement incentivizes manufacturers to simply meet the 150 g acceleration threshold. There is no incentive to further improve the energy absorption properties of the pads if they already meet the current pass/fail requirements. This limits the ability of new pad designs to further mitigate head injury risk than what is currently available. Finally, the binary outcome (injury/no injury) in relation to the 150 g acceleration thresholds prohibits graded injury risk, which would be beneficial for comparing different helmet pad responses for a variety of impact conditions.

The issues with the current uniform 150 g pass/fail standards can be addressed by a helmet safety scoring framework. Researchers at Virginia Polytechnic Institute and State University (Virginia Tech) and Wake Forest University developed a scoring system for American football helmets, which is referred to as the Summation of Tests for the Analysis of Risk (STAR) system [6]. STAR consisted of each helmet given a single score, which was based on the number of injuries that would occur in a single season if a player wore that helmet. Helmets with lower injury scores are considered safer than those with higher injury scores. The STAR system also incorporated impact exposure data into its framework, with frequent impact locations and velocities being weighed more heavily than rare impact conditions in a composite helmet score. Injury probability was assessed with a continuous injury risk function based on peak translational head acceleration during impact, which ranged from 0-100% risk of concussion.

An approach similar to the STAR rating system would address the shortcomings of the current combat helmet standards by considering an objective performance metric that expands beyond a simple/pass fail outcome. Having a system that assess performance on continuous injury risk and field exposure data would ensure the selected helmet system minimizes injuries for operational conditions of interest. This paper discusses an effort to develop a multidimensional composite helmet scoring system that can be integrated with the current U.S. Army drop tower evaluation method while leveraging prior blunt impact exposure monitoring data from theatre to inform operational exposure frequency. Not discussed in this paper, is the implementation of this multidimensional composite helmet scoring system into a user-friendly software tool.

2. METHODS

2.1 Combat Helmet Scoring Framework

The proposed combat helmet scoring framework relies on two types of information: (1) exposure weighting factors and (2) injury risk data. The exposure weighting factors represent the frequency of impact conditions a Soldier experiences for a given threat operational environment. The injury risk data represents the risk of head injury for a given impact condition. Multiplying the frequency of the exposure condition (out of 100 theoretical impacts) and the associated probability of the injury yields the number of estimated injuries for that specific condition. Summing the number of injuries for all impact conditions produces a single multi-dimensional composite helmet score for each helmet type. Rowson and Duma found it useful to renormalize the amount of impacts to a predetermined value per person per football season, such as 1000 impacts per player per season [6]. The current study assumes the composite score for combat helmet simply refers to 100 impacts for the operational environment considered. Adapting Rowson's and Duma's STAR rating equation [6] for combat helmets is as follows:

$$\text{Injuries Per 100 Impacts} = \sum_{L=1}^7 \sum_{V=1}^5 \sum_{T=1}^3 \sum_{S=1}^4 \mathbf{W}(L, V, T, S) \cdot \mathbf{R}(L, V, T, S) \quad (1)$$

Where $\mathbf{W}()$ refers to the exposure weight and $\mathbf{R}()$ refers to the injury risk. The independent variables L, V, T, S refer to the current U.S. Army drop tower impact conditions for helmet impact location, velocity, temperature, and shell size, respectively. The exposure weight \mathbf{W} will change depending on the combination of location, velocity, temperature, and shell size. There are a total number of 420 exposure weights for each combination of helmet impact location (7), impact energy (5), temperature (3), and size (4). Similarly, the injury risk \mathbf{R} will also change based on the combination of these four different variables. Equation 1 demonstrates that the weighting factor is multiplied by the injury risk for each condition, then summed across all four dimensions for a single composite score. The following sections describe the basis for \mathbf{W} and \mathbf{R} in detail.

2.2 Blunt Impact Exposure Weighting Analysis

Equation 1's exposure weight \mathbf{W} refers to the number of estimated impacts for a single combination of helmet impact location, velocity, temperature and shell size, per 100 impacts. Different operational environments will have different weighting factors. For example, a paratrooper may be more likely to impact the front of their helmet during landing compared to the crown. Therefore, all front impact locations would receive higher weightings than crown locations, which places more importance on the helmet/suspension system blunt impact response for front impacts. Determining the exposure weights for each operational environment is challenging. In their approach for American football, Rowson and Duma relied on instrumented helmet data that recorded helmet accelerations for multiple players for several games [6]. This allowed the authors determine the number of impacts each helmet locations. Rowson and Duma also conducted a series of drop tower tests with the instrumented helmet to determine a relationship between helmet acceleration and drop tower velocity, which was incorporated into their STAR framework.

The current study leveraged a similar approach with instrumented combat helmet data collected in theatre from 2013 and 2014. The second generation of the Headborne Energy Analysis and Diagnostic System (HEADSII) is a helmet mounted sensor package that measured triaxial acceleration, overpressure, temperature, and date and time. Thousands of HEADSII systems rigidly mounted to the crown location of the ACH were fielded by U.S. Soldiers, and helmet acceleration data for triggered impact events was recorded and reported in a limited distribution report [7]. In the current effort, recorded acceleration data were analysed to estimate the location of impact on the helmet, and the severity of the impact. The original dataset contained 31,103 triggered events, but the current analysis evaluated a subset of these events due to concerns about false triggered recordings and potential bias to recording impacts on the helmet's crown location. This resulted in 4,371 triggered events being selected for the exposure weighting analysis.

Impact location on the ACH helmet shell was determined by finding the x, y, and z components of the peak acceleration, and constructing an impact vector that was the opposite direction of the measured acceleration vector. The intersection of the impact vector with the ACH helmet shell geometry determined the impact location on the helmet, and triggered events where the impact vector did not intersect the helmet shell were excluded from the analysis. Impact locations coincided with the U.S. Army's drop tower impact locations over the shell's front, crown, left nape, right nape, left side, right side, and rear, as shown in Figure 1.

The HEADSII dataset was also analysed to estimate impact velocity. The ideal approach to determining the relationship between impact velocity and helmet acceleration would be to conduct a series of drop tower experiments measuring both quantities. While prior studies have measured headform accelerations during drop tower impacts, those data cannot be directly used for this study since head and helmet accelerations differ during impact. Performing such tests was not possible for the current study since the HEADSII sensors are no longer manufactured. The current study instead relied on a scaling approach that (1) assumed helmet and head acceleration followed the same relative trend with impact velocity, and (2) helmet acceleration will always be higher than headform acceleration for a given impact velocity. First, prior U.S. Army drop tower test data with an ACH were analysed to determine a relationship between peak headform acceleration and impact velocity, ranging from 2.16 m/s to 6.10 m/s, reflecting an impact energy change of 1/2x to 4x the baseline impact energy. This was done to ensure a range of impact severities from theatre were accounted for. Headform accelerations bin limits were established for each impact severity (1/2x, 1x, 2x, 3x, and 4x of the baseline impact energy). Next, the

HEADSII peak acceleration data were analysed and the majority of the triggered events from theatre were assumed to occur at a 1x impact energy on the drop tower (i.e. the majority of the triggered events were assumed to fall within the scaled headform acceleration bin at 1x impact energy). The bin limits for the HEADSII data were scaled upwards from the headform acceleration bin limits, since the helmet was assumed to experience higher accelerations than the padded headform for a given impact. The remaining HEADSII events were scaled to follow the previously defined headform acceleration-impact velocity relationship at 1/2x, 2x, 3x, and 4x the baseline impact energy bins. This resulted in each of the 4,371 recorded impacts HEADSII events coinciding with one of the potential five impact energies tested with the standard drop tower.

Translation of HEADSII Acceleration Data to Helmet Impact Location Frequency

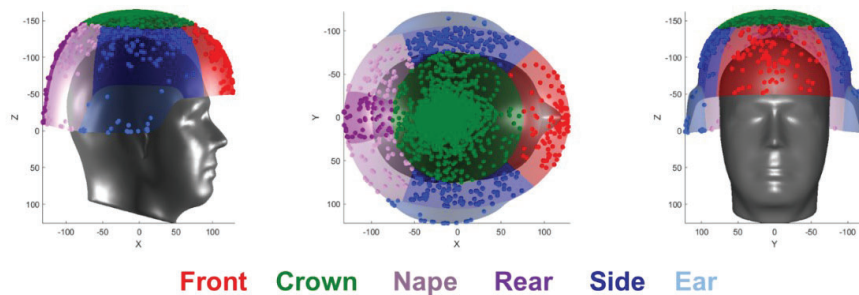


Figure 1. Examples of estimated impact location on the helmet shell taken from fielded helmet accelerometers.

Equation 1 specifies that exposure weights for different temperatures. This is important since the mechanical response of the suspension system changes with temperature, ultimately influencing probability of head injury if the impact is severe. Temperature data recorded by the HEADSII sensors for each of the 4,371 recorded impacts were recorded, and binned according to the current U.S. Army specifications (cold: 14 ± 5 °F, ambient: 68 ± 5 °F, hot 130 ± 5 °F). If a recorded temperature was between either of these three ranges, it was considered to be classified at the closest temperature range. As a result, each recorded HEADSII event was labelled as a cold, a ambient, or hot impact event.

Equation 1 calls for the weighting factors to depend on helmet size. This is critical since injury risk can be influenced by helmet size. The current study assumes the distribution of helmet sizes follows that of a recent U.S. Army helmet order. This results in the weighting factor consisting of small, medium, large, and x-large helmet shells.

2.3 Blunt Impact Injury Risk Analysis

The multi-dimensional composite score equation relies on calculating the risk of head injury for each combination of impact location, velocity, temperature, and size (see **R** in equation 1). Injury probability ranges from 0% - 100% risk of injury. There are several head injury risk functions proposed in the literature, and many rely on either linear (i.e. translational) or rotational head acceleration as a basis for injury risk. Since the current U.S. Army test standards only allow for the measurement of linear acceleration, the Head Injury Criterion (HIC) was proposed as the metric for evaluating injury probability [4][5]. HIC accounts for the magnitude and duration of the headform's accelerative response. The head injury criterion is calculated from the linear acceleration time history as:

$$HIC = \max \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt \right]^{2.5} \right\} \quad (2)$$

where t_1 and t_2 correspond to the start and end times of integration (limited to 15 ms) that maximizes the HIC value, and $a(t)$ represents the linear headform acceleration measured from impacts according to the current U.S. Army combat helmet test standards. Different helmet and pad designs will produce different HIC values for the same impact conditions. HIC values have previously been correlated to injury using injury risk curves according to the Abbreviated Injury Severity (AIS) scale [8]. The equation for an AIS 3 injury is defined as:

$$\text{Risk of AIS 3 Injury} = \frac{1}{1 + \exp\left[\left(3.39 + \frac{200}{\text{HIC}}\right) - 0.00372 \cdot \text{HIC}\right]} \quad (3)$$

Where HIC refers to the calculated HIC score from equation 2. In this instance, the risk of AIS 3 injury is considered a serious head injury, but does not predict specific injury patterns.

The current study leverages prior U.S. Army drop tower data from seven different combinations of helmet shells and suspension systems. Test data were obtained from the U.S. Army Combat Capabilities Development Command Soldier Center and the U.S. Army Aberdeen Test Center, which rely on consistent helmet positioning guidelines, such as the Head Positioning Index and retention strap specifications, to improve repeatability and reproducibility. The first two helmet systems consisted of the standard Team Wendy seven pad suspension system in an Advanced Combat Helmet (ACH) and an Enhanced Combat Helmet (ECH). The remaining five systems consisted of the ACH with five different prototype pads, all from different pad vendors. These pad systems are referred to as company A, B, C, D and E pads in the current analysis, and additional information on their design and material is found in Table 1 [9][10]. Risk of AIS 3 injury was calculated for all seven helmet/pad systems, and the resulting values were used for **R** in equation 1. The multi-dimensional composite score for each of the seven helmet/pad systems were calculated using the exposure weights (**W**) and injury risk (**R**) using equation 1. The headform acceleration data from the seven helmet/pad systems were used to calculate the HIC values for each impact location, velocity, and temperature. Since some of the helmet systems had incomplete data for size small, medium, and x-large, only size large data were used for the current analysis. This was achieved by reducing **W** to zero in equation 1 for small, medium, and x-large helmets. Additionally, HIC values were not calculated for impacts at 2.16 m/s and 6.10 m/s due to lack of data. The exposure coefficient, **W**, for these velocities were also set to zero in equation 1. The non-zero values of **W** were renormalized to sum to 100 impacts to account for the missing helmet data current analysis.

Table 1. Material description of the suspension systems analyzed in current study, taken from [9], [10]

	Suspension System Type	Number of Main Foam Layers	Materials of Main Foam Layers
Team Wendy	Individual Pads	2	Polyurethane
Company A	Hard Foamed Shell with Interior Pads	3	Polypropylene, Polyether Urethane, Polyurethane
Company B	Individual Pads	2	Polyether Urethane
Company C	Individual Pads	3	Polyurethane, Filled Silicone
Company D	Individual Pads	2	Polyether Urethane
Company E	Helmet Liner with Pads	1-3 Depending on Pad	Alkyd, Polyurethane Ethylene-vinyl Acetate, Polypropylene

3. RESULTS

3.1 Blunt Impact Exposure Weighting Analysis

The analysis of the 4,371 HEADSII events resulted in a range of impact locations, peak accelerations, and temperatures. Normalizing the 4,371 impacts to 100 theoretical impacts resulted in the exposure weights shown in Figure 2. The impact location analysis suggested that left and right sides were impacted the most frequently, with 44.4 out of 100 impacts occurring at these two locations. The crown and front were the next regions that were impacted the most frequently, with exposure weights of 14.3 and 13.5 impacts, respectively. Finally, the rear and nape had a combined exposure weight of 27.7 impacts.

The majority of HEADSII impact severities corresponded to the baseline impact energy on the monorail drop tower, with 86.6 out of 100 theoretical impacts. This result was expected since the analysis assumed the majority of the HEADSII events were comparable to a 3.05 m/s impact (i.e. the baseline impact energy). The next highest impact energy was 2x the baseline impact energy, with 10.4 out of 100 theoretical impacts. While several assumptions were made in translating helmet accelerations from

theatre to monorail drop tower impact energies, these results suggest the majority of triggered events in theatre can be represented by 1/2x, 1x, or 2x, the baseline impact energy on the monorail drop tower.

Analysis of the HEADSII temperature readings determined that the majority (92.4 impacts) corresponded to ambient temperature conditions, while the next highest temperature range reflected hot temperature conditions (7.3 impacts). This suggests that the helmet performance for ambient and hot locations should be weighed higher than performance for cold impact conditions.

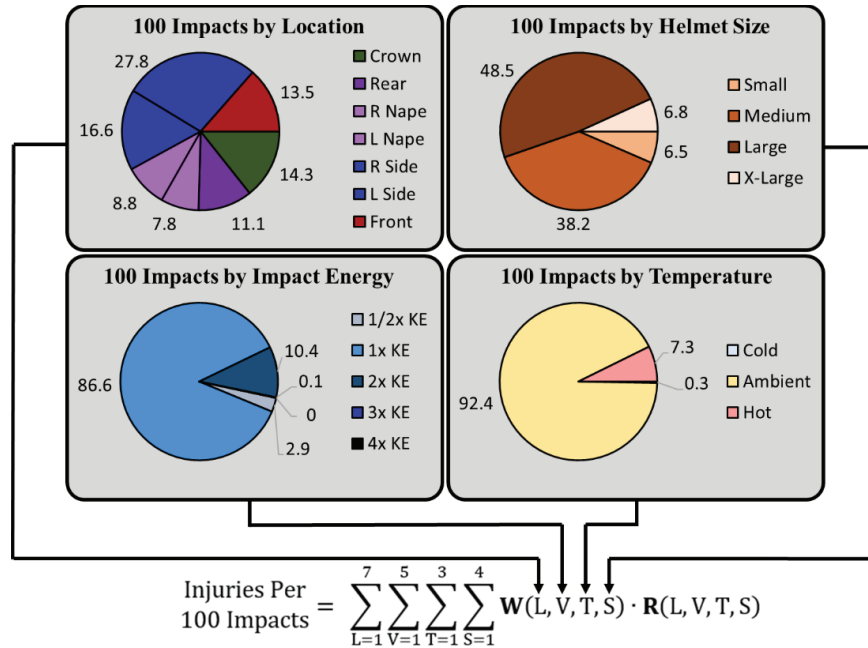


Figure 2. Weighting factors obtained through an analysis of HEADSII helmet acceleration data collected in 2013 and 2014. Numbers next to each pie wedge correspond to the number of impacts (out of 100 impacts) for each condition.

There were 420 exposure coefficients (**W**) in equation 1. These were based on the individual combinations of location, size, impact energy, and temperature. As an example, the largest exposure coefficient value was 0.108. This represented the number of impacts occurring on the size large (48.5/100) helmet's left side (27.8/100), of a 1x KE impact (86.6/100) during ambient temperature conditions (92.4/100). The second highest exposure coefficient was 0.064, and represented the same impact conditions on the helmet's right side.

3.2 Example Injury Risk Values for Helmet Drop Tower Testing

HIC scores varied with impact location, energy, temperature and helmet size. Figure 3 illustrates the range of measured HIC values for all seven helmet systems of interest for size large helmets in ambient conditions. None of the helmet suspension systems exceeded a 50% probability of AIS 3 (HIC score = 967) for 3.05 m/s and 4.31 m/s monorail impacts. The ECH with the Team Wendy pads had the lowest average HIC score for all seven helmet locations, with average values of 125 and 306 for 3.05 m/s and 4.31 m/s impacts, respectively. The worst-performing helmet varied with impact severity. At 3.05 m/s, the ACH with company C pads had the highest average HIC score (219), but the ACH with company B pads had the highest average HIC score (496) at 4.31 m/s impact velocities. Company A resulted in the highest average HIC scores at 5.28 m/s impact, with one of the seven impact locations exceeding 99% risk of AIS 3 injury. These results indicate that the relative performance of helmet systems can vary with impact location and severity.

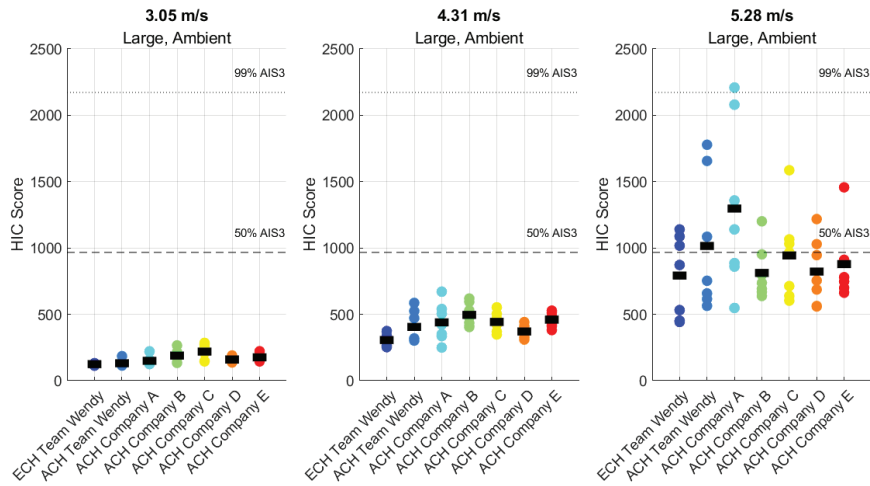


Figure 3. Range of HIC scores calculated from prior monorail drop tower test data for a mbient temperature conditions. Size large helmet data a reshown. Each coloured dot illustrates the HIC score for each of the seven impact locations at the specified impact energy, and the single black dash represents the a verage of all seven different locations for each helmet system. The two horizontal lines represent the HIC score associated with a 50% and 99% risk of AIS 3 injury, a according to equation 3.

3.3 Example Composite Scores for Helmet Systems of Interest

The composite helmet scores for each of the seven helmet systems are presented in Figure 4. These helmet scores represent the number of AIS 3 injuries that would be expected for 100 theoretical impacts with the exposure weights presented in Figure 2. Using these exposure weights, all seven helmet systems had a low number of predicted AIS 3 injuries per 100 impacts. The ECH with the Team Wendy Pads resulted in the least amount of AIS 3 injuries (1.45 injuries per 100 impacts), followed by the ACH with Team Wendy Pads (1.90 injuries per 100 impacts). The helmet/pad combination that resulted in the worst score was the ACH with company C pads (3.39 injuries per 100 impacts). It should be noted that the scores presented here are based only on the size large helmet response since the current study did not have complete test data for the other helmet sizes. These results indicate that the ACH and ECH with Team Wendy pads offer the best protection against AIS 3 injuries for the current blunt impact exposure weights used.

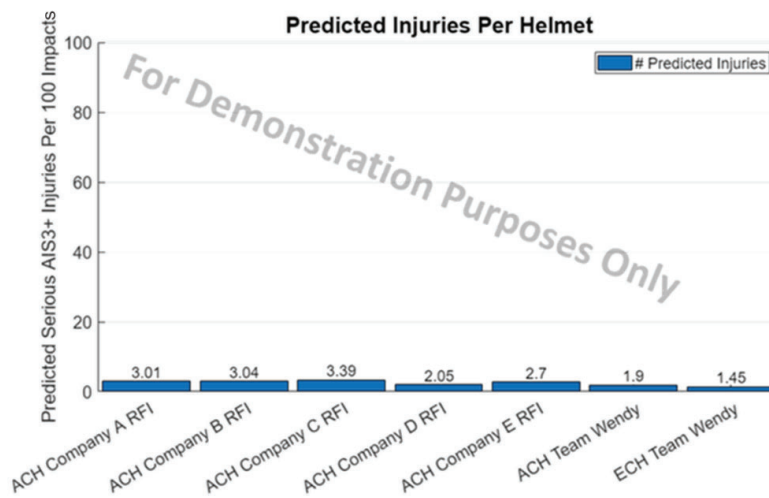


Figure 4. Multi-dimensional composite helmet scores for all seven helmet shell/pad systems. Each value represents the number of expected injuries for 100 impacts if the given helmet system is worn. A lower number of injuries (i.e. a better score) is indicative of a more protective helmet system

4. DISCUSSION

4.1 Rating Framework

The current study outlines a performance scoring framework for combat helmets based on Rowson's and Duma's approach for American football helmets [6]. The scoring framework has been modified to account for four test dimensions in accordance with the U.S. Army drop tower test methods for combat helmets: impact location, impact velocity, temperature and helmet size. The relative importance of each test condition is weighted according to combat exposure environments. Impact conditions that occur more frequently in operations are weighted more heavily in the composite score in equation 1. As an example, the ECH with the Team Wendy Pads had the lowest average HIC scores at ambient conditions for impacts at 3.05 m/s and 4.31 m/s (figure 3). This same pad system resulted in the second highest average HIC score for hot impacts at 5.28 m/s. If one were to solely examine the 5.28 m/s hot temperature condition, they may assume the ECH with Team Wendy pads performs poorly compared to the other suspension systems. However, the ECH had the best composite helmet score since the 5.28 m/s hot temperature conditions for size large helmets across all impact locations had a small weighting factor (3.5×10^{-5}) compared to 3.05 m/s and 4.31 m/s at ambient conditions (weighting factors of 0.388 and 0.047, respectively). The small weighting factor for hot impacts at 5.28 m/s resulted in this test condition have a negligible effect on the overall helmet score. This example highlights (1) the importance on selecting the appropriate set of weighting factors that represent the exposure environment of interest and (2) that solely analyzing HIC scores for single conditions may not represent the helmet system response for all conditions.

A benefit of having a single composite score for each helmet is that multiple helmets can be ranked for an exposure environment of interest, such as a mounted or dismounted operation. This is proposed as an improvement over the current standard that simply passes or fails a helmet system if it results in peak accelerations less than 150 g for all conditions. With the current standards, selecting the helmet out of a group that all 'pass' is challenging since the relative performance changes drastically depending on the test condition considered. The single composite score, which could potentially be used in addition to or in lieu of the current standard, makes this selection relatively straightforward.

The scoring system's metric of performance is the number of serious injuries (AIS 3) that occur for 100 theoretical blunt impacts in the given combat environment. The analysis of the seven different helmet/pad systems demonstrates that the number of expected serious head injuries are small for the given operational environment (<4 injuries per 100 impacts with the current exposure weights). While the current analysis only examines serious injury (AIS 3), the number of expected injuries would increase if mild (AIS 1) or moderate (AIS 2) were considered. Additionally, the number of injuries would change depending on the assumed relationship between the HEADSII acceleration values and impact velocity. The current analysis assumes the vast majority of impacts in the theatre are comparable to 3.05 m/s on the monorail drop tower, however this assumption has not been validated. If future exposure studies determine that the majority of impacts are comparable to a different impact energy, then the predicted number of injuries for each combat helmet would likely change.

One potential improvement to the injury prediction framework in equation 1 would be to evaluate specific types of head injuries based on the head's mechanical response. Early biomechanics research found a correlation between linear head acceleration and skull fracture [11], [12], while others determined that rotational head acceleration and velocity are likely responsible for brain injuries in the absence of skull fracture [13][14]. There is growing narrative that linear accelerations are correlated with skull stress (and by extension skull fracture) and intracranial pressure response, while head rotation is correlated with brain deformation (and by extension injuries such as intracerebral hematoma and diffuse axonal injury) [15][16]. The current combat helmet monorail test procedure restricts the headform's rotation during impact, so the current analysis was limited to injury risk functions that are based on translational acceleration, such as the head injury criterion. This suggests that the injuries predicted by the current scoring framework are more indicative of skull fracture rather than diffuse brain injuries. Future efforts can also measure the effect of different helmet systems on the headform's rotational response to determine how helmet and pad design potentially influence risk of brain injury, similar to the approach taken by Neice and Plaisted [17]. This would be an improvement over the current study's use of AIS specific HIC injury risk curves (equation 3), which does not distinguish between different mechanisms and types of injuries.

4.2 Exposure Weights Limitations

The relative weighting of each test condition was based on the HEADSII combat helmet acceleration and temperature data, which captured similar data as the Head Impact Telemetry (HIT) system leveraged by Rowson and Duma [6]. Prior analysis of HEADSII recordings during known operational events determined the majority of recorded events occurred in either a mounted or dismounted environment [7]. This suggests that exposure weights presented in figure 2 reflect a mixture of these threat environments. However, it remains unclear how each of the 4,371 HEADSII data recordings used to develop the exposure weights related to specific threats, such as accelerations due to blast, falls, or automotive accidents. Future data collection under different combat scenarios may lead to different exposure weights, ultimately affecting the overall helmet scores.

Preliminary analysis of the HEADSII sensor results revealed a number of challenges in data interpretations, including sensor reliability, potential recording sensitivity to crown impacts, empty helmet recordings, pairing of acceleration data to known events, and sensitivity to different helmet impact locations and impact severities. One of the biggest assumptions of the current analysis was relating the severity of impacts in theatre, via the HEADSII accelerations, to specific impact velocities during helmet drop tower testing. The current study assumed the majority of HEADSII acceleration events corresponded to impacts at 3.05 m/s, but additional work is needed to determine if this is accurate. In their scoring framework for American football helmets, Rowson and Duma conducted a series of drop tower impact tests with the HIT system, and developed a relationship between helmet acceleration and impact velocity [6]. This allowed the authors to relate in-game impacts with the HIT system to drop tower test conditions in the laboratory. A similar approach could be implemented for combat helmets, but this was not implemented for this study mainly because the HEADSII system is no longer manufactured and available to procure. Instead, future work can rely on computational models, such as finite element models, to simulate helmeted impacts with the HEADSII sensor to determine the relationship between helmet acceleration and impact velocities for different locations on the helmet shell. This relationship could be leveraged to develop improved exposure weights for the helmet scoring analysis.

Another limitation of the exposure weight analysis assumed the temperature measurement from the HEADSII sensor was valid for all pads within the helmet. The HEADSII sensor is located inside the helmet shell, underneath the crown pad. The temperature measurement is likely different than the external environment due to the body temperature of the Soldier's head. To the authors' knowledge, this difference is not well characterized. Future work can seek to characterize how temperature measurements taken inside the helmet relate to body temperature and the external environment.

4.3 Conclusion

In order to address some of the limitations of current combat helmet blunt impact test methods and requirements, the current study developed a multidimensional composite helmet scoring system for combat helmets that leverages the framework of the STAR American football helmet scoring system. Current U.S. Army combat helmet blunt impact test standards require helmet drop tower test results to not exceed 150 g for all test conditions, which include 7 helmet locations, 1 to 2 impact velocities, 3 temperatures, and 4 helmet sizes. The multidimensional composite helmet scoring framework leveraged an analysis of helmet accelerometer data recordings of impact events from theatre to determine the relative importance of each test parameter. Composite scores were calculated for seven different helmet systems by combining the exposure weights of each combination of test parameters and along with the associated the probability of head injury as determined by prior drop tower testing. The resulting composite helmet scores represented the number of estimated injuries that would result from 100 impacts with the same exposure frequency from theatre data. Data from seven different helmet/pad systems were assessed using the current combat helmet blunt impact requirement as well as using the new scoring system with improved correlation to injury, weighting based on exposure frequency, and a composite score representing the estimated number of injuries for 100 impacts. While it was difficult to determine the relative performance ranking of each helmet/pad system using the current combat helmet blunt impact requirement due to different helmets outperforming others in different test conditions, the new scoring system provided a composite score enabling a relative ranking of performance. Of the helmet/pad systems evaluated with the new scoring method, the ECH with the standard Team Wendy pads performed the best. While the current study has several assumptions behind the exposure weighting and injury risk predictions, it provides a useful framework to assess the relative performance of combat helmet systems which could be used to spur innovation and improvements in helmet systems.

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