Enhanced Blunt Impact Protection, Comfort and Stability in Combat Helmets for mild Traumatic Brain Injury Casualty Reduction

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Abstract. Low velocity blunt impact, either as a direct event (such as a fall or impact to the head) or as a secondary effect of an IED against a vehicle has become a priority for the US military. Current combat helmets provide a pad system to provide protection against a 3.0 m/s, 47 cm height (10 ft/sec, 19 inch) drop impact resulting in less than 150 G average peak acceleration to the head. As a result of the incidence of mTBI, the US military has set a 4.3 m/s (14.1 ft/s) threshold and 5.3 m/s (17.3 ft/s) objective impact criteria with the in-service Advanced Combat Helmet (ACH) and US Marine Light Weight Helmet (LWH). To provide increased blunt impact protection, one solution is to increase the standoff distance behind the shell. Due to the quantity of in-service ACH and LWH helmets however, as well as the capital investment by helmet manufacturing companies, there is no opportunity to modify or change the ballistic shell to increase the physical standoff between the helmet and head. In answer to this conflict of requirements, an impact liner system was developed to meet the 14.1 ft/sec impact standard and to dramatically increase user comfort and stability. The development and evaluation efforts towards this design are described. Test results against the current and future ACH and LWH indicated an average peak acceleration of approximately 100 G at 3.0 m/s (10 ft/s) and 140 G at 4.3 m/s (14.1 ft/s). In future designs, modifications to the impact test protocols are recommended to reflect real world impacts and better designed test equipment methodologies.

1. INTRODUCTION

With the incidence of mTBI in recent conflicts, the US military have proposed a threshold impact protection criteria for the in-service ACH and LWH of 4.3 m/s (14.1 ft/s), <150 G average peak acceleration and an objective criteria of 5.3 m/s (17.3 ft/s), <150 G. In response to these requirements, a Spaceframe Improved Pad Suspension System (SiPSS) was developed by PSP to increase blunt impact protection to 4.3 m/s without reducing stability or comfort. Various user human factor issues are presented with design changes of the liner with an existing ballistic shell, as well as effects upon legacy soldier equipment such as goggles, communications headsets and so forth. The ability to design a retrofit liner system aimed at an existing ballistic shell required consideration of both human factors or operational as well as impact performance.

The SiPSS consists of a permanent one-piece impact management liner and headband system suspended with a spaceframe structure. Highlights of some performance and operational features of the helmet sub-system are discussed in the context of the greater demands placed on today's ballistic helmets and test methodology required for their evaluation.

Figure 1: The SiPSS impact management and headband system.

2. HUMAN FACTORS AND OPERATIONAL ISSUES

2.1 Retention and Stability

The design of the helmet retention system has evolved over the past years as the demand for functionality has grown. Early use of chin straps was primarily to serve the purpose of helmet securement, ensuring that head protection was in during impact. The requirements have since evolved to include helmet stability so as not to have the shell obstruct the wearers' vision and to ensure adequate head coverage. With the more recent use of helmet mounted hardware such as night vision goggles, visors, beacons and facial protection systems, the demands for stability has further increased to ensure their proper operation.

The methodology to assess helmet securement is well defined in existing helmet performance standards for transportation, sports and some ballistic helmets, typically involving quasi-static or dynamic loads imposed on the chin strap. Performance requirements either specify the degree of allowed elongation, need for mechanical integrity or resistance to helmet roll-off to ensure that securement is obtained during loading of the helmet. These requirements are typically satisfied with the proper selection and placement of webbing materials and hardware. Performance may also be influenced by strap geometry, compression of liner or padding materials and slippage of the straps through buckles and fastening hardware.

The above evaluation methods, however, do not include stability criteria as the primary objective of the standards is to address severe impact events and not loads encountered during operations. As such, a new stability test methodology was developed to account for offset or oscillatory loads that may be present from helmet mounted hardware. The test method requires that a tangential quasi-static load be applied to a helmet's lower edge and, while under load, helmet rotation be measured.

The SIPSS was developed incorporating a unique headband geometry to engage the head in a more effective manner thereby providing greatly improved stability. Headband contact above the glabella and below the opisthocranion helps engage the head around its maximum circumference thereby providing better engagement. The SiPSS system was tested according to the new test methodology and compared to a standard ACH retention and pad system. Varying amounts of slack were introduced into the SiPSS to ensure realistic tensioning of the headband. The results of forward and rearward stability tests are shown graphically in Figure 3 and Figure 3, respectively.

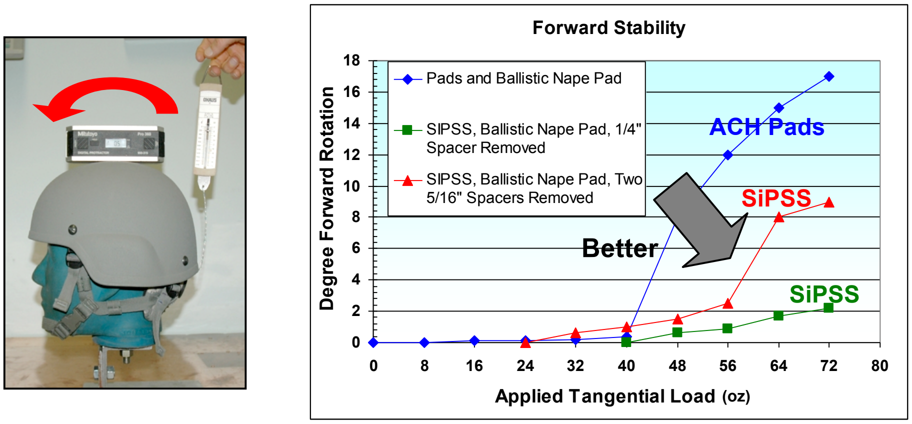

Figure 2: Forward helmet stability test method and results.

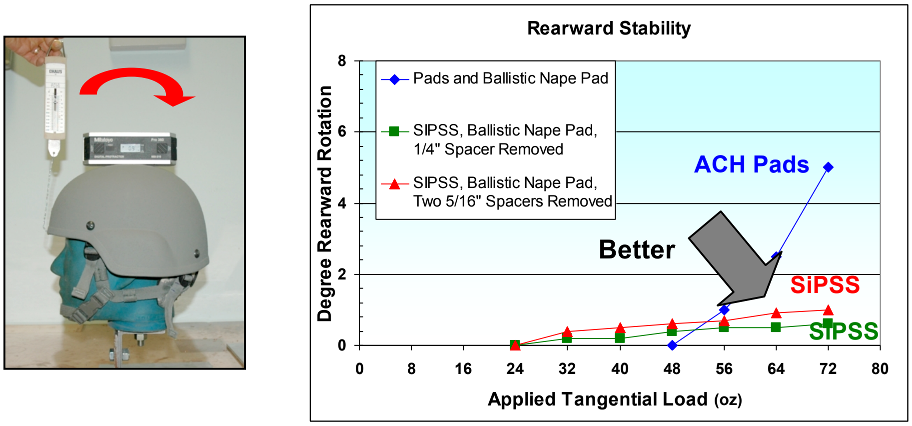

Figure 3: Rearward stability test method and results.

The test results indicated that even with the ballistic nape pad addition in place, greater helmet stability is achieved for the loads applied. It is anticipated that this should result in better operational performance of helmet mounted devices.

2.2 Comfort and Fit

While often treated as a secondary requirement, the comfort and fit of a helmet is critical to proper function and protection by ensuring its continued use. The overall objective to achieving physical comfort and fit is to limit pressure points on the head. This can be achieved by, first, having a helmet sized to provide adequate offset from the head and, secondly, conforming the helmet liner to the shape of the head to achieve good load distribution.

Both of the above objectives were achieved with the SiPSS headband suspended by a spaceframe structure shown in Figure 1. The flexible character of the headband allows it to naturally conform the wearer's head regardless of shape. In comparison to foam fit pad systems, the headband circumference is the only adjustment required. This was achieved with a custom dial fit system which allows the full range of a helmet shell size to be utilized without the need for loose fit pads. Even pressure distribution is achieved along its periphery with sole adjustment of the headband tension. While excellent comfort is achieved with a low tension setting, it can do so without sacrificing helmet retention due to the shape of engagement with the head as discussed previously. A crown pad system is also employed to provide support of the helmet weight on the head.

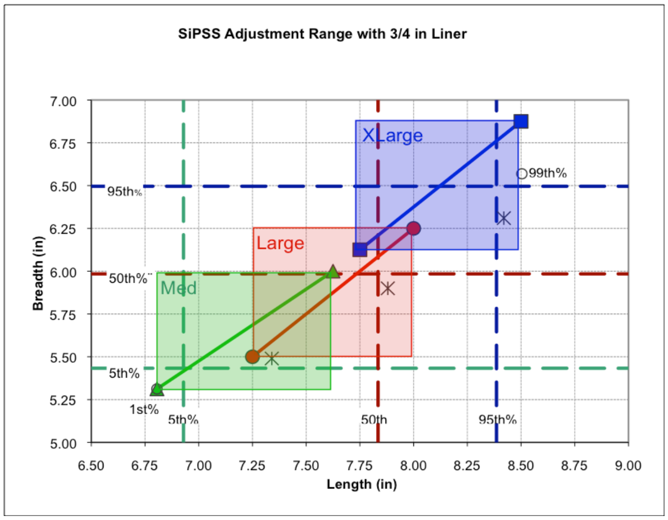

Figure 4: Adjustment range of SiPSS within the ACH shell sizes.

An example of the adjustment range within the existing range of ACH helmet shell size increments is demonstrated in Figure 4. It can be seen that a wide range of head sizes and shapes can be accommodated with the integral liner and headband system.

2.3 Heat Retention

In order to determine any undesired thermal burden, the SiPSS liner was tested in comparison to a standard ACH at the EMPA in Switzerland on sweating head manikins, Figure 3. Testing involved an ACH with standard pads and an ACH fitted with the SiPSS liner. The climate chamber was conditioned to 22°C (71°F) at 50% relative humidity and the headform to 35°C (95°F). The testing assessed the ability of the helmet system to allow heat transfer from the head (*forced convective heat loss*) while facing an airflow of 1.45 m/s (4.7 ft/s), equivalent to walking speed.

Figure 5**.** Test configuration with Large ACH helmet facing airflow (from left)

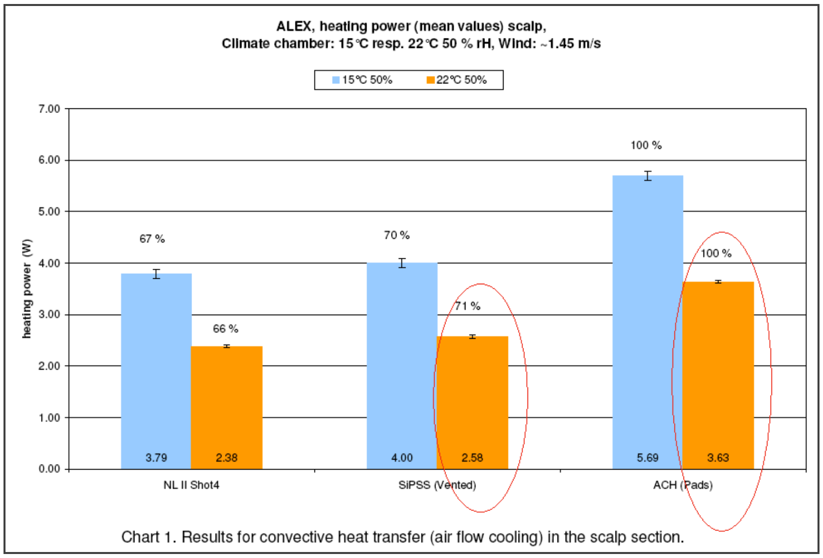

Chart 1. Results for convective heat transfer (air flow cooling) in the scalp section.

Figure 6**.** Test results chart for ACH with pads, ACH with SiPSS and ACH with vented SiPSS

The results shown in Figure 4 indicate that the ACH with pads is 29% more effective at transferring heat at 22°C (71°F) compared to SiPSS. This is due to the gaps around the pads to allow air to move the heat away. A key element of the test is that when the air temperature approaches skin temperature (35°C/ 95°F) the forced convective heat loss will drop to zero. Therefore on operations in Afghanistan for example with daily temperatures above 45°C (113°F), the type of helmet liner will not affect how hot the users head gets. The remaining issues become comfort, abrasion, sweat absorption or the psychological feeling of heat. In human subject trials, Zhang et al. (2007) noted that facial thermal sensation had a greater impact on the thermal sensation of the rest of the body [1]. Anecdotally with the head, soldiers typically may feel hotter but are not physiologically hotter.

3. BLUNT IMPACT PROTECTION

The ACH blunt impact protection specification [2] requires an impact velocity of 10 ft/sec of a helmet and headform onto a hemispherical anvil. The resultant acceleration should be less than 150 G when tested in the hot (55^0C), cold (-10^0C) and ambient (21^0C) temperature conditions. The 10 ft/sec impact criteria are derived from potential injuries during parachute landings. US parachutes descend at a rate between 14 ft/sec and 23 ft/sec for the MC1-1c and TC-10C parachutes. An impact of 10 ft/sec would be consistent with a poorly executed landing with a descent rate of 14 ft/sec. Similarly a 14 ft/sec impact represents an 18 ft/sec descent rate[3].

Recently the US Army announced an R&D goal for helmet blunt impact of 14.1ft/sec and 17.3ft/sec in place for the existing 10ft/sec requirement whilst maintaining the average and peak acceleration to below 150 G. It is this requirement that initiated the helmet impact liner research and development by PSP and Biokinetics.

3.1 Impact Test Protocols

Performance requirements stipulated in the military helmet standards affects the design and implementation of the ballistic helmet systems. As a result, specific shell, impact liner and retention components are utilized to meet the protection and operational requirements. In a similar fashion, the test methods and protocols can also have an affect helmet designs whether or not they are intended to reflect actual requirements. Helmet attachment method, test sequence and test locations are specifically discussed in the context of the SiPPS development efforts.

3.1.1 DOT Test Headforms and Helmet Securement

The current ACH test protocol is a variant of the Federal Motor Vehicle Safety Standard (FMVSS) 218 and were not initially intended to test combat helmets. The standard specifies the use of U.S. Department of Transport (DOT) headforms. The headforms, initially designed for the evaluation of helmets for motor vehicle users do not have a chin. Combat helmets have a retention system or chin strap as a main security and stability system for the helmet. Without a chin on the headform, the helmet cannot be used as designed during an impact test due to rotation or shifting of the helmet during impact. Artificial securement means are therefore employed and can vary from laboratory to laboratory. Proposed modifications can be seen in Figure 7 Further, additional specifications are required to determine the chinstrap tension during impact. Such data should be derived from user trials utilizing load cells to identify average load at each of the 4 chinstrap retention locations on the shell.

3.1.2 Double Hit Criteria

In the ACH test protocol, the standard mandates 2 impacts each at 7 various locations on the shell within 2 minutes of each other. This is intended to represent the ability of the impact material to recover between impacts and continue to provide multi hit protection. In real world impact events, it is highly unlikely to receive an impact at the same site and with the same velocity and energy. Whilst this standard provides reproducible data for evaluation, it is not representative of a battlefield impact injury. Furthermore, the double impact requirements limit the range of impact management materials that can be used as some recovery of the impact liner is required prior to the second impact for the current application. Recoverable materials generally tend to be less efficient than non-recoverable ones thereby limiting the protection level achievable. Several current U.S. DoD programs have opted for a specification using a single impact anywhere on the helmet shell.

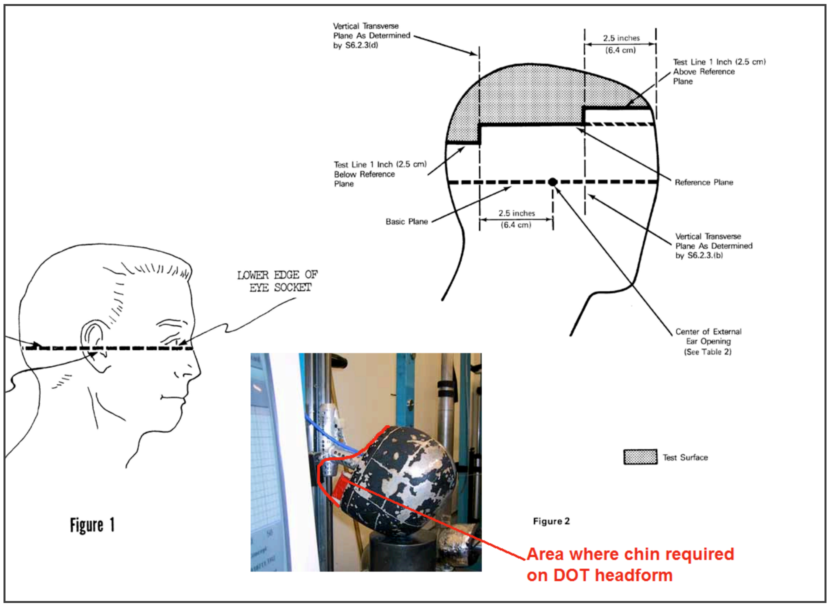

Figure 7: DOT headform chin deficiencies.

3.1.3 Impact Location Criteria

U.S. Special Operations Command (SOCOM) have recently decided to use a test specification that has 7 standard ACH impact locations on the helmet as a baseline test standard to compare various impact products and materials. SOCOM has also elected to use a test standard allowing an impact anywhere on the ballistic shell including areas where there is no impact protection or traditional pad inside the shell. Such a test represents a truly field representative condition and should be used in conjunction with specified locations. Testing of ACH helmets with SiPSS liners has shown a clear trend in impact variance according to helmet location. This is primarily due to the geometry and ballistic shell curvature at the point of impact as well as the available area loaded under impact. Frontal impacts were seen to produce higher acceleration compared to crown, side and rear impact locations.

3.2 Impact Material Developments and Considerations

3.2.1 Helmet Offset

The ACH uses 4 sizes of ballistic shell from small to extra large. In order to develop a retrofit impact liner which maintains the head sizing criteria for the helmet, an offset of 19 mm (0.75 in) was the only available space between the head and inside of the ACH shell. Given that impact performance is a function of helmet offset, impact velocity and mass, only materials that could function adequately at the 19 mm thickness were considered. Ideally, the impact layer should be developed before the ballistic shell, thereby not constraining design to a pre-determine space claim. Only commercially available materials were considered for use due to the time constraints of the project.

3.2.2 Multi hit Recoverability

Due to the ACH double impact requirement, materials were selected and tested for their ability to recover sufficiently within the time constraint to provide second hit impact performance. Non-recoverable materials such as Expanded Polystyrene (EPS) foam were not selected. Vinyl Nitrile (VN) foam was considered as an optimum material but later discarded due to its degraded impact performance above 50°C. Expanded Polypropylene (EPP) bead foam produced favourable results across several varied foam densities. EPP exhibited good multi hit performance across the temperature range and had a small difference between the average and maximum peak acceleration. The exact EPP grade and densities used in SiPSS are not presented due to proprietary constraints.

3.2.3 Heat and Cold Effects on Impact Performance

The ACH specification environmental conditioning tests in the hot (55°C), cold (-10°C) and ambient (21°C) temperature conditions produce further impact performance variance for the same shell locations from helmet to helmet. Where a material solution may pass the 150 G requirement in the hot condition, the same test material conducted in the cold will often fail. For foam materials, this is due to the temperature stiffening effect on the liner and shell with reduced temperature. In development, this leads to a delicately balanced or "tuned" material solution to cater for all impacts and environmental conditions.

3.2.4 Materials Manufacture and Processing

Materials also had to be considered for their ease of manufacture in a finished design. The approximate cost of the finished ACH is $200 USD, with ACH pads costing approximately $30-40 USD. An impact liner therefore requiring significant capital equipment expenditures was not desirable. Whilst VN had moderate impact performance, the standard process of heat molding a liner reduced the impact performance. EPP proved to be easily fabricated using steam injection molding and produced repeatable results for impact testing but has higher capital equipment costs. In development, the cost of tooling for EPP became a significant issue in finalizing designs.

3.2.5 Materials Summary

Overall, injection moulded EPP demonstrated the best repeatable multi hit impact performance at 4.3 m/s (14.1 ft/s) as compared to other materials. It's one drawback is the relatively high manufacture cost related to injection moulding cavities required for each liner size, Table 1.

Table 1: Summary **of m**aterial selection results.

Material Type	**Impact Performance**	**Multi-hit Criteria**	**Manufacture Cost**
EPP	High	High	Moderate
VN	High	High	High
EPS	High	Low	Moderate
Moldable VN	Moderate	Moderate	High

3.3 Impact Results

3.3.1 SiPSS EPP Liner Impact Results

The SiPSS EPP liner was tested according to the ACH specification at 4.3 m/s (14.1 ft/s) in each temperature condition across a range of densities and design styles to determine the most optimum performance. The results can be seen in Figure 8 and Table 2 with comparison to the existing ACH pads testing conducted by the U.S. Army [4]. Traditionally, the hot condition impact test requirement has been the most challenging to meet due to material softening and the headform completely compressing the impact liner thereby hitting the underlying helmet shell. In order to fully optimize a liner system for 4.3 m/s (14.1 ft/s), material density sacrifices had to be made to enable adequately reduced accelerations for ambient and cold tests. This resulted in a liner that whilst did not pass both average and maximum peak accelerations within 150 G, provided consistent performance across all impact locations and temperatures. The average accelerations for SiPSS in all conditions at 4.3 m/s (14.1 ft/s) was 153 G compared to 160 G for standard ACH pads. The average of maximum peak accelerations was 179 G for SiPSS and 286 G for ACH pads.

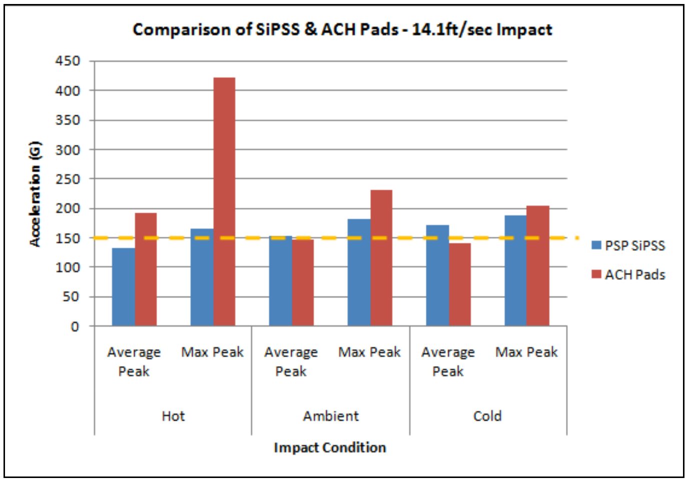

Figure 8: Summary of 4.3 m/s (14.1 ft/s impact results compared to the ACH.

Table 2: Impact variance between average and maximum peak acceleration (impact performance consistency).

	Hot		Cold		Ambient		Average Variance	
	Variance (G)	Variance (%)	Variance (G)	Variance (%)	Variance (G)	Variance (%)	Variance (G)	Variance (%)
SiPSS	32	19%	28	15.4%	17	9%	25.7	14.6%
ACH	228	54%	86	36.9%	63	30.7%	125.7	40.6%

4. SUMMARY AND DISCUSSION

The average and peak accelerations for impacts up to 4.3 m/s (14.1 ft/s) can be reduced close to the required 150 G injury threshold with current materials and within the space constraints of the existing ACH helmet shell. Developmental testing has shown that an impact liner made from EPP exhibits the optimum performance across all temperatures, impact locations and multiple hits. Further development is required in simulation and modeling of helmet impact at 4.3 m/s (14.1 ft/s) in order to optimize the available materials. Additional research is required in the development and alteration of existing foam and polymer structures at a molecular level to enhance performance in temperature extremes.

Helmet stability, comfort and fit requirements were defined to meet the general operational and functional requirements of ballistic helmets. Where required, test methodologies were developed and used to assess a unique suspended headband retention and fitting system (SiPSS). The new system demonstrated improved performance over a typical ballistic helmet in use today.

References:

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[4] B. Joseph McEntire and Katie Padgett, "Blunt Impact Performance of USMC LWH and US Army ACH with Fielded and Alternative Fitting Systems", USAARL Technical Memorandum. December 2006.