Novel Tactical Ballistic Shield Technology:
A Blast Injury Mitigation Evaluation

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Abstract:

This study investigates the performance of a shield appliqué technology designed to protect the user from blast injury. This technology was compared against three other ballistic shields of varying mass using a fixed charge configuration. An instrumented anthropomorphic test dummy (ATD) was used along with pressure sensors to determine injury risk. Results showed that lighter shields offered less protection than their heavier counterparts with higher probability of head, chest, arm and leg injuries. Additionally, when comparing the appliqué to a mass‑matched shield, relevant loadings were reduced on average by 21 %. Overall, the ballistic shield appliqué technology shows promise for becoming a tool for blast mitigation in the short to medium term.

Keywords:

1. Introduction

Historically, much effort has been devoted towards protecting structures [1, 2] and vehicles from blast [3, 4] while individual protection has been typically limited to bomb suits [5] and ballistic protection [6]. With the advent of lighter technologies, the introduction of a portable blast shield is fast approaching. A pioneering technology, tested in the context of this study, aims to reduce blast impulse and pressure in order to decrease the severity and number of injuries caused by blast exposure.

Blast exposure injury is divided into multiple categories. Primary blast injuries include effects of blast overpressure and shock loading [7]. Often more subtle than other injury mechanisms, primary blast injuries can appear as gradual changes in cellular behaviour [8]. Secondary blast injuries are caused by penetrating ordinance and fragmentation. Existing ballistic shields technology may offer some degree of protection against high velocity fragmentation but are currently designed for protection against

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specific classifications of firearms [9] and do not consider blast as their primary operating environment. The materials used and overall design of these shields are to stop the effect of high-pressure differential created by penetrating ballistic bullets that have relatively minimal momentum [10, 11]. Further, a shield designed primarily for ballistic purposes may actually increase the severity of injury caused by the blast environment such as has been discovered with ballistic vests integrating Kevlar [12, 13]. Other sources of injuries due to explosives include tertiary blast injury such as the result of a fall or collision with another object, including the shield itself. Meanwhile, quaternary blast injury refers to injuries related to the chemical effects of the blast. Primary and tertiary blast injuries are the main focus of this study.

Although shield technology designed for the blast environment has applications in theatres of war where exposure to blast is most prominent; para-military, domestic, and civilian applications are also to be considered [14]. Civilian firefighters and police bomb squads are two potential users of such an advanced technology [15]. From home grown terrorism to international threats, United States citizens are faced with blast threats nearly 5 times per day [16].

The most likely scenarios pertain to the mitigation of risk when intelligence of suspected vehicles or buildings is positive for explosives. Perhaps the most readily available application of blast rated shield technology is during breaching activities as the type and quantity of explosive would be known and therefore precise protection could be designed for and used regularly by special team members.

Current individual protection from blast is primarily limited to explosive ordinance disposal (EOD) suits [17]. Although this currently represents the best (and only) option for blast protection, it does not allow for rapid deployment nor ease of use and reduces human function and mobility.

The aim of the study is, therefore, to examine the risk mitigation potential of new blast shield appliqué technology. To do so, the effect of different shields on user injury is considered across a range of shield configurations.

2. Methods

The testing presented in this report focuses on a system level approach to comparing the performance of a new portable ballistic shield appliqué (termed Advanced Impulse Reduction or AIR) to a range of shields of different mass by using a full-scale use scenario. The nature of the shield was the only manipulated variable in the test series while every other element was kept constant. The primary outcomes observed are differences in stress and loadings to the user's body. These loadings were then discussed in the context of injury probability as correlated to various injury criteria, injury biomechanics and injury literature.

Described in Tab. 1, the test groups were designed to allow for comparison on the basis of mass and technology. Mass modulated shields were made out of E-Glass sheets (Fiber-Tech Industries Inc., Ohio), a fiberglass material rated for ballistics protection. Across all test groups, the handle used was made of aluminium and the surface area of all sample groups was constant.

As shown in Fig. 1, the test setup involved an explosive charge placed centrally with a shield held by an instrumented anthropomorphic test dummy (ATD) and four pressure sensors symmetrically positioned on both sides of the charge.

Tab. 1 Test conditions descriptions

Test Group	Description	Mass
Light Weight	Made from a quarter-inch E-Glass sheet and a handle.	10.9 kg
Half Weight	Made from a half-inch E-Glass sheet and a handle.	20.0 kg
Full Weight	E-Glass sheet and a handle, made from a half-inch panel and an additional quarter-inch panel that was trimmed to match the mass of the AIR shield.	27.2 kg
AIR	Impulse reducing technology (AIR) adhered to thin E-Glass panel with handle using Velcro.	27.2 kg
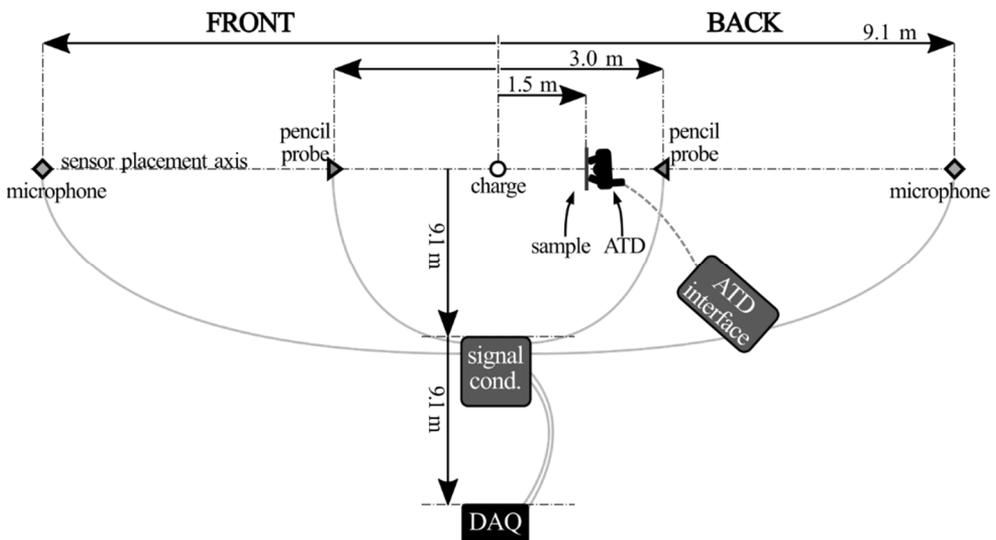
Fig. 1 Test setup layout

The test charge consisted of a 1 kg sphere of C-4. This plastic explosive was molded into a spherical shape by hand and subsequently wrapped with tape in order to keep the charge together. The charge was primed with a non-electric shock tube detonator of number 8 strength with a 450 ms delay. The shock tube lead line was 30 feet long and had a transfer explosive made up of aluminized HMX.

The charge was suspended at the same height as the shield's Centre of Mass (CofM), 70 cm vertically above the test stand (ground). The distance from the shield to the charge was determined horizontally from the CofM of the shield to the centre of the charge. In order to ensure proper height and horizontal distance to the sample, the C-4 was also tied to a fixed point on the ground in addition to its suspension point.

The ATD used for this test was a Hybrid III 50th percentile male dummy (Humanetics, Plymouth, USA) equipped with a chest mounted Slice Nano data acquisition system (Diversified Technical Systems, Novi, Michigan) and outfitted with tactical clothing. This ATD came equipped with multiple accelerometers, angular rate sensors,

load cells and a chest deformation displacement sensor. An additional pressure sensor[1] was also fixed to the dummy in an orthogonal orientation to the shield in order to determine general ATD overpressure exposure. The complete list of signals and filters for the experiment can be consulted in Tab. 2.

Tab. 2 List of signals and filters

Signal	Filter
Head Acceleration X / Y / Z	CFC1000
Head Angular Rate X / Y / Z	CFC180
Upper Neck Force X / Y / Z	CFC1000
Upper Neck Moment X / Y / Z	CFC600
Chest Acceleration X / Y / Z	CFC1000
Chest Deflection	CFC600
Pelvis Acceleration X / Y / Z	CFC1000
Left / Right Femur Force Z	CFC600
Left / Right Tibia Force Z	CFC600
Lumbar Spine Force X / Z	CFC600
Lumbar Spine Moment Y	CFC600
Overpressure	None
Front / Back Incident Pressure	None
Front / Back Microphone Pressure	None

The chosen ATD instrumentation and signal-filtering scheme followed both the Allied Engineering Publication 55 (AEP-55) [18] and the Defence Science and Technology Laboratory (DSTL) recommendations [19]. In addition to the recommendations of these two similar standards, three angular rate sensors were added in the head of the ATD; this addition allowed to calculate the severity of acceleration induced brain injury more accurately.

Using an electrically isolated platform, the ATD was partially suspended with paracord so that both feet were firmly on the ground. The ATD was then placed in a crouched "tactical" shield use position behind the test shield sample. For the first test, the dummy was placed in the position shown in Fig. 2, height was recorded and feet were positioned, and then outlined using bright spray paint to ensure the identical stance was used in subsequent trials. Additionally, each upper limb was placed into the typical grasping position of the shields handle and documented using photography.

Blast pressure pencil probes[2] were placed 10 feet from the charge, both in front and behind the test sample. Both were placed on metal stands 2 feet off the ground and oriented to point directly at the charge. The sensitive region of each pressure probe was covered with dielectric tape and the cables were mechanically isolated from the steel

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[1] High frequency ICP® pressure sensor 102B15 (200 psi) from PCB Piezotronics, Depew, NY.

[2] Quartz free-field Blast Pencil Probe 137B22B (500 psi) and 137B24B (250 psi) from PCB Piezotronics, Depew, NY.

stands using foam strips. Two microphones[3] were also positioned 30 feet from the charge in either direction, on the same axis and in the same manner as the pressure sensors.

Fig. 2 ATD support and bracing position against sample

All pressure signals were acquired at a rate of 100 kS s^{-1} [4] by National Instruments CompactDAQ[5] system while the injury data was sampled at a rate of 20 kS s^{-1}. Pressure data acquisition was triggered via a threshold on the pencil gauges and time synced via a break wire positioned on the charge itself. Meanwhile, the ATD's data acquisition module was triggered using a manual trigger routed from the ATD interface box to an operator, behind a shelter.

High-speed video footage of each trial was also recorded. The images were acquired at 30 000 frames per second using a Vision Research Phantom v2511 (New Jersey, United States). The camera was positioned orthogonally to the sensors' axis and therefore, in a plane parallel to the shield.

Using the video footage, changes in the shield position were measured. These measurements were then converted to shield velocities and accelerations which were then used to calculate loadings to non-instrumented regions of the ATD.

Statistical analyses were carried out using JMP Statistical software version 12.2. A one-way analysis of variance was used to compare the mean responses between groups. The analysis was carried out for each response variable separately. The variable group was considered to be a fixed effect factor in the model. Post hoc tests using the Tukey-Kramer adjustment were used to compare the mean responses for each pair of groups. All of the standard model assumptions concerning the residuals were verified;

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[3] High Amplitude Microphones 378A12 from PCB Piezotronics, Depew, NY.

[4] kS is kilo Sample.

[5] NI CompactDAQ 8-Slot USB Chassis, NI cDAQ-9178 from National Instruments, Austin, TX.

the residuals should be normally distributed, and centred about zero with constant variance. In cases where the residuals from the models were not normally distributed non-parametric tests using the Wilcoxon test were used.

3. Results and Discussion

Ten trials were completed for each of the three heaviest shield conditions and five were performed for the Light Weight shield. From the data collected, focus was put on the signals that related to injury and those which show the greatest difference between each condition. The results and relevant discussions are presented in a separate examination of each body part and its associated mechanism of injury.

3.1. Overpressure

The overpressure shockwave magnitude was determined by measuring the pressure behind the shield at the thigh area of the ATD. This pressure was measured as significantly higher in the Full Weight shield trials ($p < 0.05$) and lowest using the AIR technology appliqué. The lighter shields results averaged approximately 15 % higher than the AIR shield, although this difference was not significant ($p > 0.05$).

Tab. 3 Overpressure results

Test Condition	Overpressure μ ($\mu-\sigma$ — $\mu+\sigma$) [kPa]
Light Weight	295.6 (254.5 — 336.8)
Half Weight	303.9 (256.1 — 351.6)
Full Weight	445.3 (304.6 — 586.0)
AIR Shield	255.8 (139.9 — 371.6)

Although most loading types described in this section are specific to one limb or body part, overpressure has an impact on a wide range of organs [20]. Using literature on the impact of blast on brains [21], lungs [22] and eardrums [23], overpressure results can be correlated to risk of injury for each aforementioned structure.

Eardrum injuries are a common occurrence in any theatre of war [24], since they occur at a lower pressure differential than lung or brain injury. Tympanic membrane rupture has been known to occur in pressure differentials as low as 35 kPa and as high as 100 kPa [25]. However, in order to correlate the measured reflected overpressure to injury, a conversion to incident overpressure was necessary. This was achieved using the known properties of C-4 air blasts using the Conventional Weapons Effects [26] (ConWep) model.

Once converted, the incident overpressure magnitudes can be seen breaching the injury threshold (35 kPa) across all conditions. All but the AIR shield condition also breached the 100 kPa limit for which almost all eardrums rupture as reported by Stewart et al. [25]. In the case of the AIR shield, the pressure differential does not breach the upper limit of 100 kPa, however, the pressure mitigation is insufficient to reduce all risk of injury.

Based on the same overpressure, injury corridors for the brain [21] and lungs [22] were suggested by Rafaels and Bass [27]. These injuries were determined using pulse magnitude and duration normalized to TNT scale. Pressure differentials of all conditions

lie well below available injury curves, suggesting the overpressure was not sufficient to cause more than eardrum damage as detailed above.
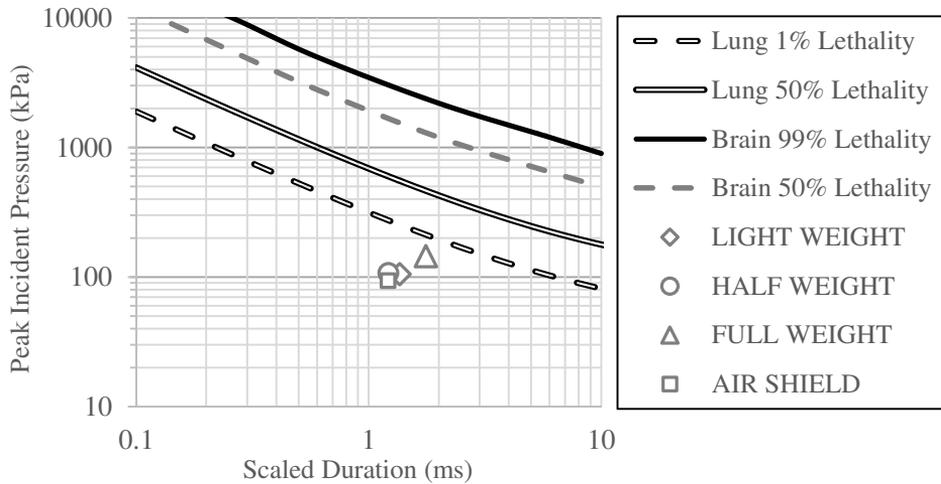
Fig. 3 Brain and lung overpressure tolerance

3.2. Head and Brain / Injury

Tertiary blast injury of the brain and head originates from excessive acceleration of the skull rather than overpressure exposure. Angular and linear accelerations can be applied to the Head Impact Power (HIP) [28] score in order to be correlated to acceleration-based injury.
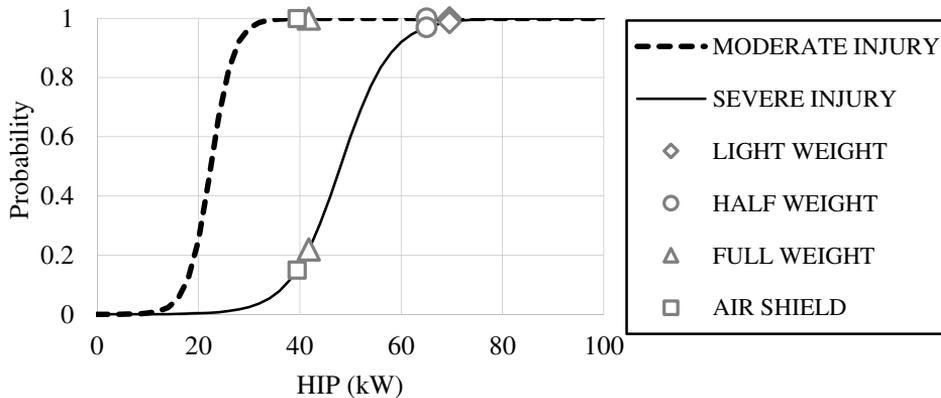
Fig. 4 HIP score correlated to injury risk curves across all conditions

Using clinical data [29], the HIP score has been linked to moderate and severe neurological injuries. Moderate neurotrauma can be described as loss of consciousness of less than 24 hours but more than 30 min. The same study also suggests this classification of injury can be described as a Glasgow Coma Scale (GCS) score between 9 and 12. Meanwhile a severe neurotrauma would imply a loss of consciousness that would exceed 24 hours [30], which could also be expressed as a GCS score between 3 and 8.

As seen in Fig. 4, the results correlate to a high probability of severe neurotrauma (99 % and 97 %) in the Light Weight and Half Weight conditions meanwhile, the probability of the same injury is lower for the mass matched shield (22 %) and even lower for the AIR shield (15 %).

The position of the dummy and the shape of the shields tested may best explain the harmful magnitude of these head accelerations across all conditions. As shown in Fig. 5, the head was positioned in such a way that the helmet was exposed to the charge. This exposure may have unnecessarily increased the risk to the head and brain. A more prone position or a higher shield might have mitigated this exposure.
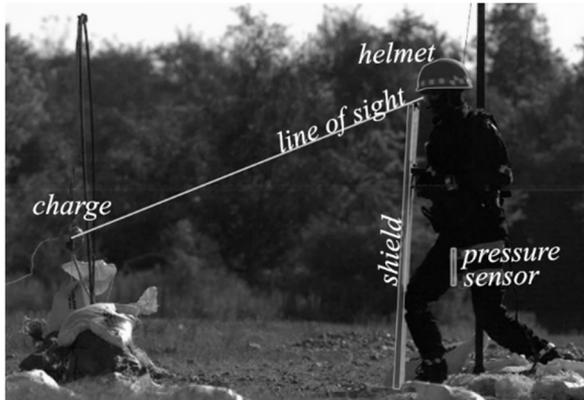
Fig. 5 Head exposure beyond shield

3.3. Neck Injury

To quantify the stress to the neck, the three forces and moments of the cervical spine were consolidated into the N_{ij} criterion. Through injury data collected by the automotive industry [31], the loadings to the neck can be correlated to different levels of injury codified as part of the Abbreviated Injury Scale (AIS) [32-34] as shown in Fig 6.
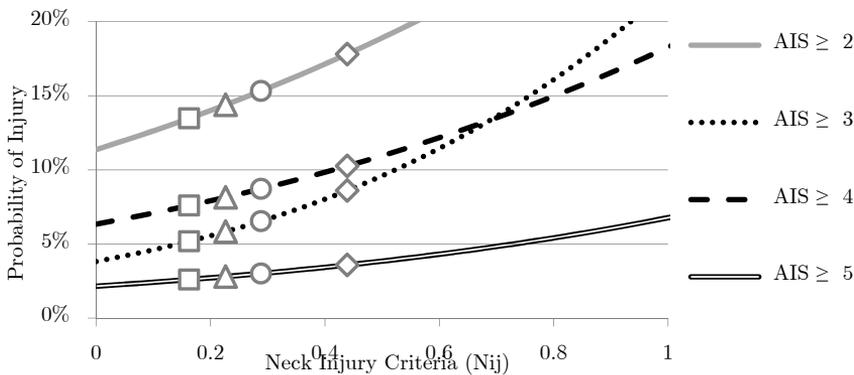
Fig. 6 Risk injury curves for Neck Injury Criteria

The highest risk of neck injury comes from the lightest of the shields, which shows a risk of up to 18 % for injuries classified as AIS 2 or more. These injuries are considered moderate and consist of a dislocation or fracture of the spinous or transverse process of

the cervical spine or minor spinal compression. Other shields reduce the risk of such injuries down to 15 %, 14 % and 13 % for each of the progressively heavier shield and finishing with the AIR technology appliqué.

At a score of AIS 3, injuries are considered severe but not life threatening. Contusions to the larynx and pharynx are reported as well as further, more severe, compression, dislocation and fracture of the cervical spine. At a score of 4, laryngeal crush and incomplete cervical level spinal cord lesions are observed while complete spinal lesions belong to AIS 5. At the same AIS level 5, damage to the carotid artery is also reported, starting with intimal tear or thrombosis with and without neurological deficit. As reported in Fig. 6, these more severe injuries are unlikely, with the Light Weight shield offering the highest risk at 4 % for AIS of 5. Meanwhile, for heavier shields, the risks of severe injuries (AIS 5) remained at approximately 3 %.

Though these findings suggest a low but non-negligible risk of significant injury, the improvement across conditions appears marginal. Proportionality between mass and performance can nonetheless be observed within this improvement.

3.4. Chest Injury

By combining peak chest deflection and deflection rate as a result of shield contact with the torso, the Viscous Criterion (VC) developed by Lau and Viano [35] can be used to infer the risk of thoracic injury. The use of loading rate in this criterion reveals the dynamic properties of the chest as higher loading rates may be fatal even at relatively low displacement.

Based on the injury probabilities inferred from VC and shown in Tab. 4, usage of the Light Weight shield carries a 50 % probability of severe chest injury and a 38 % probability of critical abdominal injuries. However, risk of injuries is shown to decrease to 10 % and 8 % probability for the Half Weight and Full Weight shields. Meanwhile, the chest injury risk associated with the AIR technology appliqué was half that of the Full Weight shield.

Tab. 4 List of signals and filters

Test Condition	Viscous Criteria [ms⁻¹]	Probability of Severe Chest Injury	Probability of Critical Abdominal Injury
Light Weight	1.30 ± 0.35	50 %	38 %
Half Weight	0.66 ± 0.31	10 %	Minimal
Full Weight	0.61 ± 0.23	8 %	Minimal
AIR Shield	0.42 ± 0.18	4 %	Minimal

In this situation, severe chest injuries may include many combinations of rib cage fracture, and lung damage. Contusion or laceration of the lungs can lead to accumulations of blood or air in the mediastinum or in the chest cavity, creating a hemothorax or pneumothorax (or hemo/pneumomediastinum) [36]. Various tears and lacerations to the central vascular system and trachea are also included within this category. Meanwhile, critical abdominal injuries relate to complex ruptures of abdominal organs such as the liver, spleen, kidneys or pancreas or major lacerations of the gastrointestinal tract. Injuries to those organs are considered to be life threatening but would be less likely in this case considering that the thoracic contact position of the handle during testing is higher on the torso than abdominal organs.

3.5. Upper Extremities Injury

Although the Hybrid III ATD is not equipped with any sensors reporting the state of the upper extremities, results dependent on shield movement were measured through video analysis as shown in Table 5. Also, using measured shield peak acceleration; an inertial loading to the forearm was calculated by using the assumption that the arm is fixed at the elbow due to the bracing position. This calculation results in a peak bending load to the user's forearm which is highest using lighter shields and decreases to 755 and 560 N for the Full Weight shield and AIR shield respectively.

Tab. 5 Upper extremities results

Test Condition	Peak Shield Movement Rate μ (μ–σ — μ+σ) [ms^{-1}]	Peak Forearm Bending Load μ (μ–σ — μ+σ) [N]
Light Weight	10.1 (8.7 — 11.5)	1491 (1173 — 1809)
Half Weight	6.4 (5.6 — 7.2)	894 (608 — 1180)
Full Weight	4.6 (3.8 — 5.3)	755 (512 — 998)
AIR Shield	4.9 (4.8 — 5.0)	560 (383 — 737)

In order to correlate these results to injury potential, the peak movement rate of the shield is assumed to equal user forearm movement, which has been correlated to injury by Hardy et al. [37]. In their study, the research group explored the outcome of airbag deployment on upper extremities and were able to establish that the probability of injury increased sharply past 15.2 ms^{-1}. Though this scenario correlates well to the blast shield situation, the peak movement rates measured are well below Hardy's limit.

Though this criterion suggests that the forearm would remain uninjured, the bending load of the arm suggests otherwise. Using the bending strength of the radius and ulnar reported by Nahum and Melvin [38], a loading of 1 200 N can be used to represent a probability of injury of 50 %. The loading involved in Light Weight shield tests, as reported in Tab. 5, exceeds this 50 % probability. Loadings obtained for other shields suggest a much lower likelihood of fracture, especially for the AIR shield, which was calculated at less than half of the 50 % probability value. Exact risk could not be calculated as only a mean value and range of data were reported.

3.6. Lower Extremities Injury

Across the lower extremities, loads to the right leg were 5 to 14 times higher than the loads to the opposite leg. The loadings were especially high for the right side femur of the Light Weight and Half Weight shields as they exceeded double the average load of the AIR shield.

An initial assessment of the injury risk can be made using load limits for the long bones of the leg and the compressive loadings collected by the ATD. Multiple values are reported for the femur and tibia strength based on different study conditions. A limit developed for use with the Hybrid III ATD by Mertz et al. [39] suggests fractures at 9.07 kN while a more general criteria by Levine et al. [40] suggests a limit of 7.72 kN for the femur (Fig. 7). Meanwhile, tibial injury criteria associated with compressive loading start at 5.4 kN, which is twice as high as the highest loadings measured in the current study for either tibia.
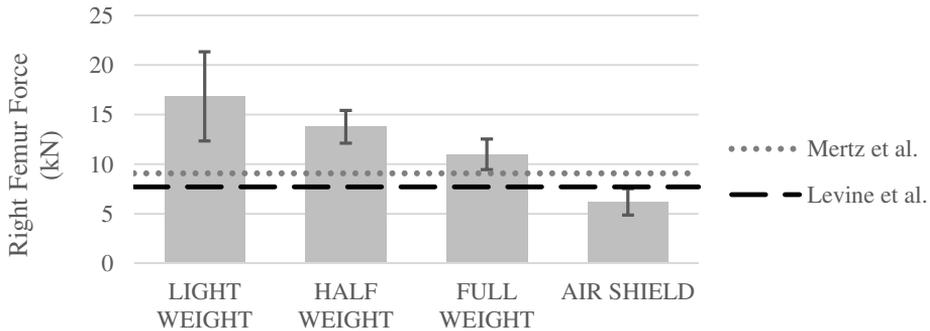
Fig. 7 Femur results with injury criteria

As shown in Fig. 7, all shields except the AIR shield breached both femur injury criteria. In fact, 8 out of 10 AIR shield trials remained under the lowest limit of 7.72 kN, while all trials from other shields were above the higher limit of 9.02 kN. This suggests a much higher risk of femur fracture when using the non-AIR shields.

Additional insight into the injury can be obtained via the knee-thigh-hip criterion developed by Rupp et al. [41]. This criterion can be used to further define the location and probability of injury. To do so, Rupp's method uses the impulse calculated from the Hybrid III force readings to determine the location of the injury. This finding is further supported by similar research [42], which concluded that the rate of axial loading of the spine defines the location of the injury. With a more aggressive loading rate, the injury is more likely to be located proximally to the point of application of the force as the bone is unable to transmit the force along its length prior to failure.

For all conditions, impulses calculated using femur data clearly pointed to high-rate/short duration loadings for knee-thigh-hip injuries as defined by Rupp. This translates into patellar and distal femur fractures. In addition, based on the peak force readings, the probability of injuries suggested by the knee-thigh-hip criterion for the Light, Half and Full Weight shields is 90 %, 80 % and 45 % respectively. Meanwhile, the risk of knee and distal femur injury when using the AIR shield is only 8 % (Fig. 8).
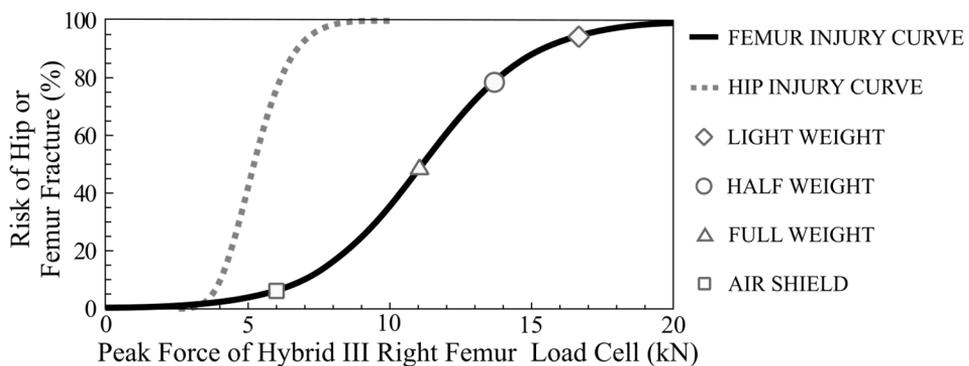
Fig. 8 Knee-thigh-hip criteria results

The ipsilateral risk of injury in this case can be attributed to the bracing position of each leg against the shield. The left leg was placed in support, behind the user. Meanwhile the right leg was braced against the shield using the knee. Though this provided

stability and support to the shield, it also placed the knee at higher risk for injury as a large amount of the blast impulse was transmitted through the shield and to the right side knee.

3.7. Impulse and Polytrauma

While impulse reduction is an overall measure of performance for blast mitigation technology, impulse is also a metric directly related to injury severity [43]. The impulse measured using the load at the right knee shows a degree of proportionality between the impulse reduction and mass of the shield. This finding, illustrated by Fig. 9, is expected, as greater inertia should result in lower shield acceleration that in turn generates lower impulse at the knee. For the same mass however, the Full Weight shield and AIR technology shield would be expected to generate a similar impulse. However, a 28 % difference can be seen between the two test groups, suggesting that the AIR technology appliqué absorbs, deflects or otherwise dissipates the energy directed at it, further protecting its user.
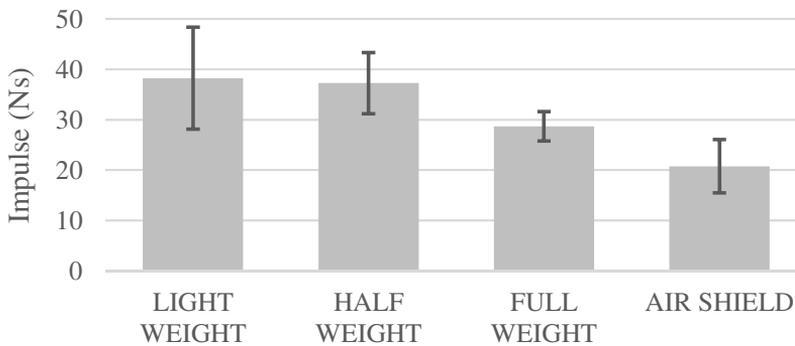
Fig. 9 Impulse results

This protective performance is best illustrated by the cumulative polytrauma associated with each shield condition. As the mass of the shield increased, the number of injuries and their severity decreased. However, at the same mass, the Full Weight E-Glass shield was out performed by 21 % on average by the AIR technology. As shown by impulse data, the performance of the AIR technology cannot be simply attributed to its mass. The technology does not appear to be operating as a typical rigid body, rather it appears to be mitigating the threat through other properties of the material.

This difference in loadings has important implications on the overall state of the user after a blast. The largest improvement seen between the two mass matched conditions comes from the loading applied at the right knee, which was reduced by 43 % in the AIR technology appliqué. This difference would allow the user to maintain mobility; an aspect that can be vital to surviving a threat.

However, none of the shields tested protected the user from tympanic membrane rupture or loss of consciousness. Caused by the overpressure and head acceleration, these two consequences of the blast severely impede proper response to the threat. Though ear protection and a shield design that prevents direct exposure of the head could be used in order to reduce risk, more research is required to confirm if these modifications would be sufficient to eliminate injuries.

4. Conclusion

Generally, the ballistic shield appliqué technology shows promise for becoming a tool for blast mitigation in the short to medium term. Specifically however, this blast shield technology could be designed immediately to mitigate most risk in well-defined scenarios such as breaching. In order to further quantify the performance of such shields against less survivable threats, additional testing using a lower standoff or larger charge would be advisable. More testing would also help inform the design of such shields when it comes to injuries related to fragmentation or other secondary blast injuries.

Acknowledgement

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