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Development of a Multimodal Blast Sensor for Measurement of Head Impact and Over-pressurization Exposure

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Abstract—It is estimated that 10–20% of United States soldiers returning from Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) have suffered at least one instance of blast-induced traumatic brain injury (bTBI) with many reporting persistent symptomology and long-term effects. This variation in blast response may be related to the complexity of blast waves and the many mechanisms of injury, including over-pressurization due to the shock wave and potential for blunt impacts to the head from shrapnel or from other indirect impacts (e.g., building, ground, and vehicle). To help differentiate the effects of primary, secondary, and tertiary effects of blast, a custom sensor was developed to simultaneously measure over-pressurization and blunt impact. Moreover, a custom, complementary filter was designed to differentiate the measurements of blunt (low-frequency bandwidth) from over-pressurization (high-frequency bandwidth). The custom sensor was evaluated in the laboratory using a shock tube to simulate shock waves and a drop fixture to simulate head impacts. Both bare sensors and sensor embedded within an ACH helmet coupon were compared to laboratory reference transducers under multiple loading conditions ($n = 5$) and trials at each condition ($n = 3$). For all comparative measures, peak magnitude, peak impulse, and cross-correlation measures, R^2 values, were greater than 0.900 indicating excellent agreement of peak measurements and time-series comparisons with laboratory measures.

Keywords—Concussion, Brain injury, Military, Blast, Head.

INTRODUCTION

To date, more than 1.6 million soldiers have served in the wars in Iraq (Operation Iraqi Freedom—OIF) and Afghanistan (Operation Enduring Freedom—OEF). Traumatic brain injury (TBI), specifically blast-induced TBI (bTBI), has become the signature injury of modern warfare and is the greatest cause of mortality and morbidity of those deployed soldiers. Because of the high risk to life, researchers have historically focused on the cause, treatment, and methods for preventing moderate and severe TBI, but, with improvements in protective equipment resulting in greater survivability, this focus has recently shifted toward understanding the same aspects for mild traumatic brain injuries (mTBI). While the exact frequency is unknown, it is estimated that 10–20% of all returning soldiers have suffered at least one instance of bTBI.[11] Owing to the complexity of these injuries, onset of symptoms may not be initially identifiable, posing an immediate threat potential to both the injured soldier and surrounding personnel. Furthermore, soldiers returning from duty frequently report persistent symptoms associated with long-term effects of mTBI, commonly referred to as post-concussion syndrome, which can decrease quality of life and contributes to a growing body of evidence supporting the existence of deleterious blast effects.[7] The relatively high prevalence of bTBI in deployed military personnel has highlighted the need to develop better protection and detection methodology. In order to accomplish this task, we first must gain a better understanding of the etiology of bTBI, beginning with quantifying the trauma producing exposure to the head following a blast event in theater.

Detonation of explosive devices such as shells, grenades, and improvised explosive devices (IEDs) cause extreme pressures to expand from the detonation origin and compress the surrounding air to generate a pressure pulse, or blast wave,[22] that diverges spherically and decreases in pressure and intensity as it propagates away from the origin. As a result, the most

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severe primary blast injuries often occur at the locations closest to the point of detonation. Four mechanisms of injury are commonly associated with these blast events.[4] In order of temporal occurrence, the initial injury mechanism is exposure to the over-pressureization wave with fluid-filled organs, such as the lungs and bowels, the most prone to injury. Secondary injuries are caused by projectiles or related shrapnel, which are propelled by the pressure wave, and which penetrate the body. Tertiary injury occurs following blunt impact with surrounding surfaces (e.g., ground, walls, etc.) following body translation, and, finally, quaternary injuries may occur from high temperature exposure, radiation, or other correlated risk factors. Of these potential mechanisms of injury, over-pressurization and blunt impact are most often associated with bTBI.[7]

While quantifying blast exposure is necessary to determine injury etiology, it has proven difficult to replicate the highly complex and variable environment experienced by a soldier through laboratory reconstructions or open-field simulations. Ideally, soldiers could wear instrumentation to record these events in-theater which could be used as input to laboratory parametric studies using Finite Element or blast tube models[2,3]; however, direct measurement of over-pressurization and blunt impact in live combat situations has been significantly limited by the lack of high-fidelic exposure measurement, storage, and power technologies available in field-ready form factors. In the laboratory, high-sensitivity pressure transducers sampled at high frequencies (>1 MHz) are required to measure and record over-pressurization waves. When simultaneous measurements of both over-pressurization and blunt impact are necessary, the measurement system complexity and cost is expanded even further. Head acceleration was first established as a primary indicator for severe TBI[1,9,10] and has since been shown to be strongly correlated with mTBI following blunt impact in sports[8,19,20]; however, traditional systems for measuring head acceleration in the laboratory require a minimum of six,[14,25] but more practically nine,[15,18] linear accelerometers placed in specific orientations and locations relative to the head center of gravity. While accurate and repeatable under controlled conditions, these reference systems are not practical for in-theater use because multiple transducers are required for understanding blast pressure measurements due to potential variation in body orientation relative to blast origin (incident vs. reflected measurements); accelerometers placed on the helmet shell are prone to noise and do not provide a true measure of force experienced by the head; and miniature, high-frequency, multi-channel data acquisition systems capable of being borne by soldiers are both costly and have power requirements limiting use over long periods of time.

In a first attempt to overcome these obstacles, the Army mounted sensors on 6000–7000 Advanced Combat Helmets (ACH) worn by soldiers between 2008 and 2009.[5] The helmet-mounted sensor arrays recorded acceleration at the point of placement via a tri-axial accelerometer and unidirectional overpressure following a triggered event which included everything from a nearby explosion to a dropped helmet. The device was capable of storing 500–600 events locally which could then be downloaded to a consolidated database for review. To date, no data have been reported from this effort; therefore, it is unknown how well the system overcame the previously identified technical limitations as well as potential performance limitations that include (1) sensors were mounted directly to the helmet without head contact providing measures of helmet acceleration which have been shown to be uncorrelated with head acceleration measures used to evaluate risk of injury[13]; (2) measures of over-pressure are highly directional, and so, without additional knowledge of pressure wave direction, unidirectional sensors are inadequate for accurate quantification of the pressure wave; and (3) since no local processing was available, differentiating between actual and false triggers (e.g., dropped helmets, non-blast events, etc.) is difficult unless a secondary form of verification is available. Owing to the practical, technical, and performance limitations of current methodologies employed to characterize trauma-producing blast exposure, development of alternative sensing technologies and methodologies to implement them in-theater is required.

The aim of this study was to evaluate the capability of using a single sensing technology to simultaneously measure over-pressure and blunt impact. Specifically, we created a custom electret film sensor and evaluated it under simulated over-pressurization and blunt impact conditions by comparing the custom sensor output with measurements obtained from laboratory reference transducers. Conditions selected were intended to simulate primary and tertiary injury mechanisms that may result in mTBI during non-lethal blast exposure. Moreover, we developed a method for differentiating blunt impact events from over-pressurization events using output from this single custom sensor.

MATERIALS AND METHODS

A series of bench-top characterizations were conducted to evaluate the performance of a custom sensor under various simulated impact and over-pressurization conditions. Outputs from the custom sensor were correlated with laboratory measures for both peak and impulse signal. The custom sensor was designed to simultaneously measure both impact and over-pressurization, interface to low-power electronics, and be potentially retrofittable to existing military helmets.

Custom Sensor

The custom sensor (Fig. 1) is created from a flexible electret film that proportionally releases electrostatic charge under both compression and deflection. The film's high flexibility, low density, and low acoustic impedance are ideal characteristics for retrofitting into existing helmets and provide excellent air-coupling to allow for over-pressurization measurements. The electret film (75-μm-thick polypropylene) was printed with conductive silver ink on both sides of the film to create electrodes that could capture generated charge from the film and transfer this charge to the analog electronics. To create uniform consistency across the sensor, conductive silver ink (Creative Materials 200-05) was silkscreened onto the electret film and cured at 112 °C for 4 min. The cured electret with silver ink was die cut into a rectangular strip (width = 1 cm, length = 15 cm) and covered on both sides with 50.8 μm pressure-sensitive adhesive backed by 76.2 μm polyester film. Electrical leads were attached to the electrode surfaces on each side of the sensor and connected to a high-impedance ($>10^{12}$ ohm), high-gain bandwidth (1 MHz) voltage follower amplifier (Maxim 9917) before analog-to-digital conversion (500 kHz sample rate; National Instruments USB 6531). A custom application written in LabVIEW (National Instruments, Austin, TX) was created to collect, display, and save raw data to file for post-processing.

Over-pressurization

Simulated pressure waves were created with a 2.1-m-long (OD = 7.62 cm, ID = 5.08 cm) calibration shock tube (PCB Electronics, Model 901A10). The shock tube expansion chamber was filled with compressed air until a replaceable diaphragm of mylar sheet clamped between the expansion chamber and shock tube exceeded bursting strength. An aluminum mounting block placed 1.90 cm past the shock tube end was fitted with a reference transducer (Endevco 8530B-500) to provide a gold-standard reflective pressure measurement for these evaluations. The reference pressure transducer signal was passed through a gain amplifier (Endevco 136) connected to the same data acquisition system as the custom sensor, allowing for simultaneous sampling of both signals. Data collection for both sensors was triggered when the reference transducer exceeded 6.9 kPa with 20 ms of data collected pre-trigger and 180 ms collected post-trigger.

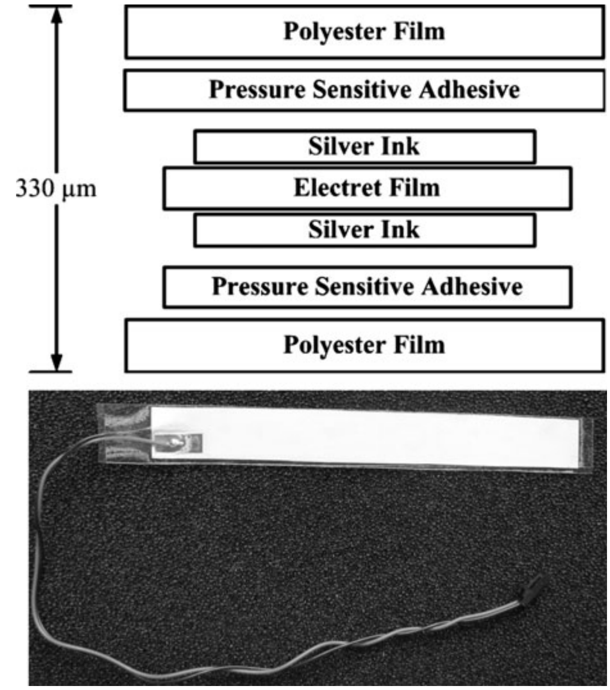

FIGURE 1. A custom sensor was created from a flexible electret film to simultaneously measure both impact and over-pressurization. The sensor was tested under simulated conditions and compared to reference sensors to evaluate its performance.

The sensor-mounting block provided the flexibility for testing two custom sensor-mounting conditions. In the first condition, a bare custom sensor was adhered directly below the reference sensor with both sensors being on the same plane normal to the shock tube opening (Fig. 2a). A second mounting condition was then evaluated to simulate the integration of custom sensors within a helmet. For this second condition, a custom sensor was adhered to the inside surface of a helmet coupon (6 × 8 cm cutout of an ACH shell). The helmet coupon was then attached to the mounting block with a 1.90-cm trapezoidal helmet pad (Oregon Aero, 95080-G) placed between the custom and reference sensors (Fig. 2b).

Five levels of peak reflective over-pressure were evaluated by varying the thickness of the diaphragm material. Target driver pressures required to generate a pressure wave for each material thickness were 103.4, 206.8, 482.6, 792.9, and 1103.1 kPa. Parameters for the maximum test condition were selected to simulate bare sensor (603.7 kPa) and in-helmet pressure (31.7 kPa) obtained from open-field blast trials using 0.45 kg of C4 explosive at 1.45 m away from the point of detonation, which is an approximation of a small

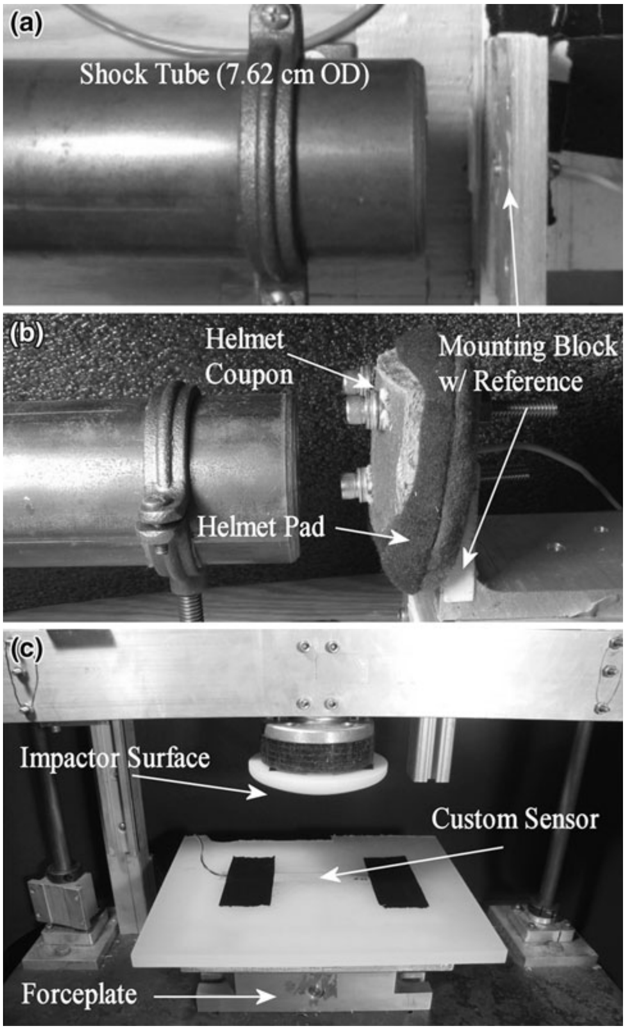

FIGURE 2. The custom sensor was evaluated under simulated over-pressurization and blunt impact conditions. A bench-top shock tube was employed to create pressure waves. The bare sensor configuration placed both the reference and custom sensor in the same plane and directly in front of the shock tube opening (a). For the in-helmet configuration, the custom sensor was placed in between the helmet coupon and helmet pad, while the reference sensor remained in the mounting block directly behind the foam pad (b). A twin-rail linear drop tower was employed to simulate blunt impact events with the reference forceplate placed directly below the custom sensor (c).

improvised explosive device (IED) in close proximity. The remaining trials were selected to provide a distinct range of pressure for these evaluations. Three trials were conducted at each level for both mounting conditions, yielding fifteen total trials per mounting condition.

Blunt Impact

Blunt impact events associated with tertiary injury (i.e., blunt impact with surrounding surfaces) were simulated using a twin-rail linear drop test fixture with a 5-kg impactor drop arm and hemispherical impactor surface similar to those used in football helmet testing (Fig. 2c).[16] A custom sensor was placed on a 2.54-cm-thick vinyl nitrile foam pad secured to the surface of a force plate (AMTI, MC6-6-4000) positioned directly below the drop test fixture. For all trials, a thin (0.64 cm thick) vinyl nitrile foam layer was placed over the surface of the custom transducer to prevent sensor damage during impact. The custom transducer signal was buffered using the same signal-conditioning board as that used in the over-pressurization evaluations. Both the custom sensor and force plate were connected to a high speed data acquisition system (National Instruments, PCI 6024 with BNC 2090 breakout box) and simultaneously sampled at 100 kHz. Raw data were sampled, visualized, and saved to ASCII files using a custom LabVIEW application.

Five levels of impact energy were generated for this evaluation by dropping the impactor arm from heights of 5, 10, 15, 20, and 25 cm above the custom transducer which corresponded to impact energies between 2.45 and 12.26 J. The minimum drop height was selected to simulate the applied forces either at or above that which exist between the ACH helmet shell and foam insert (i.e., similar to the in-helmet over-pressure configurations) during a blunt impact associated with diagnosed concussion in sports. The remaining conditions were selected to provide a distinct range of force output without damaging the custom sensor. Three trials were conducted at each drop height for a total of 15 blunt impact tests.

Signal Differentiation

As an alternative to dedicating custom transducers to either over-pressurization or blunt impact measurement, a method of signal conditioning was developed to capitalize on these two types of events falling into distinct regions of the frequency spectrum. Specifically, a complementary filter was constructed to extract signals of interest in the frequency domain from data collected during the shock tube and linear drop tests. One channel was designated as a low-pass filter and the other as a high-pass filter with both filters set to the same cutoff frequency.

For the purposes of this evaluation, a first order Butterworth filter was chosen as an exemplar technique, primarily because of its simplicity and potential for in-theater application since this method can be replicated with a single pole RC circuit. Moreover, the Butterworth filter has the added features of maximal flatness in the pass band and a 20 dB/decade roll-off in the stop band.

Data Analysis

All data from the custom and reference transducers were post-processed and analyzed using a custom Matlab script (version 7.11, The MathWorks Inc., Natick. MA). To determine an acceptable cutoff frequency for the complementary filter to differentiate blunt impact from blast events, residual frequency analysis (Fig. 3) was conducted on all laboratory tests by comparing the ratio of signal distortion to noise passed through the filter between 10–200 Hz for blunt impacts, and 10–4000 Hz for blast impacts in 10-Hz increments on the channel of interest.[24] The primary benefit of residual frequency analysis is that it provides the ability to evaluate the filtering effects on each signal at multiple cutoff frequencies, particularly in the transition region between signal distortion (denoted as line *bc* in Fig. 3) and noise passed through of the filtered signal (denoted as line *cd* in Fig. 3). The optimal cutoff frequency for each trial was chosen by selecting the point where the ratio of normalized signal distortion to normalized noise passed through did not exceed 0.5. Mean and standard deviation of cutoff frequencies for each condition were calculated, and, based on these results, a single cutoff filter frequency was selected to differentiate between blunt impact and blast events. Data from the custom sensor (all test conditions) were filtered using the single selected cutoff frequency with signal retained from the low-pass filter channel used for comparison with the blunt impact reference and signal retained from the high-pass filter channel used for comparison with the over-pressure reference.

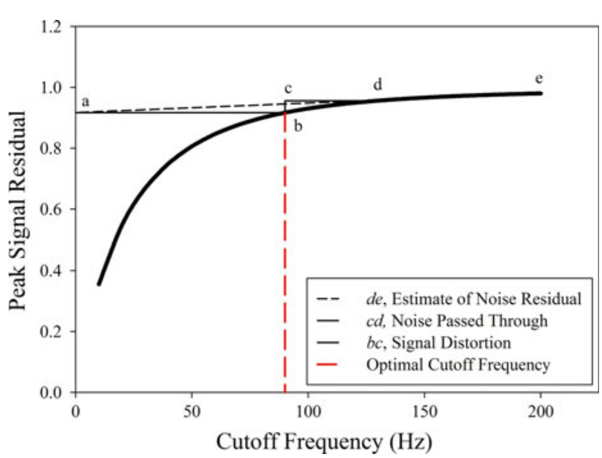

FIGURE 3. The optimal cutoff frequency for a complementary filter to differentiate blunt impact from blast events was determined through residual frequency analysis. The peak signal residual (ratio of peak signal retained after filtering) was calculated across a range of potential cutoff frequencies. The noise residual (*de*) was estimated for all potential cutoff frequencies using the optimal cutoff frequency (red dashed line) for each trial identified by selecting the point where the ratio of normalized signal distortion (*bc*) to normalized noise passed through (*cd*) did not exceed 0.5.

For single event comparisons, over-pressure data from the reference transducer was filtered using a zero-lag low-pass Butterworth filter (order = 1; Fc = 125 kHz) while blunt impact data from the force plate was filtered using a zero-lag low-pass Butterworth filter (order = 1; Fc = 10 kHz). Time series data from both transducers were then truncated to 5 ms (1 ms before peak signal and 4 ms post peak signal), 10 ms (3 ms before peak signal and 7 ms post peak signal), and 30 ms (10 ms before peak signal and 20 ms post peak signal) time windows for bare sensor over-pressure, in-helmet over-pressure, and blunt impact trials, respectively. This process eliminated any potential influence of signal artifact occurring before or after the primary over-pressure or blunt impact event. Using the truncated signals, peak- and time-integrated (impulse) transducer outputs were then extracted with custom sensor outputs quantified by charge (pC), reference pressure transducer output in units of pressure (kPa), and force plate output in units of force (N).

Correlation of peak and impulse outputs from the reference and custom sensors was evaluated using regression analysis with goodness of fit, R^2, classified *a priori* as excellent (≥0.95), good (0.94–0.85), moderate (0.84–0.75), and poor (≤0.74). In addition, cross-correlation of scaled and synchronized time history measurements was conducted for each test to measure the similarity of the custom sensor time-history data with the reference transducer. For correlation of the time-history profile independent of magnitude, charge outputs from the custom transducer for all time points were scaled using the ratio of peak output between the custom and reference transducer.

RESULTS

Peak reflective pressures measured by the reference sensor ranged between 92.1–666.1 kPa and 9.9–47.9 kPa for all trials of the bare sensor and in-helmet conditions. For in-helmet tests at the lowest driver pressure evaluated (103.4 kPa), the reference sensor did not exceed the data collection threshold of 6.9 kPa due to the significant shockwave attenuation caused by the helmet shell. Because of this, results from the in-helmet condition are inclusive of only twelve trials while the other conditions consist of 15 trials. Peak force measured by the reference sensor ranged between 752–1823 N for all blunt impact tests. Mean optimal cutoff frequencies for the custom sensor found by residual analysis for in-helmet over-pressure, and blunt impact were 167.5 Hz (SD 39.1; range 120–240), and 90.7 Hz (SD 2.6; range 90–100), respectively. The residual analysis did not identify an optimum cutoff frequency for bare sensor over-pressure within the range of frequencies applied in the simulation (10–4000 Hz). Upon inspection of the filtered data, the optimal cutoff filter for peak signal is well beyond this evaluated range; however, the dissipation phase of the signal begins to be distorted. Because of this, an optimal cutoff filter is dependent on the metric of interest (peak vs. impulse), and since the purpose of this initial analysis was to simply evaluate an approach for identifying a cutoff filter that would differentiate blunt impact from blast events, extending the analysis to a higher range of frequencies was unnecessary. Based on these results, a cutoff frequency of 80 Hz was selected and applied to custom sensor data for all trials. By choosing a cutoff frequency slightly below the optimal cutoff frequency for blunt impact only, we expect a small amount of blunt impact signal loss, but, in turn, allow greater differentiation between blunt impact and in-helmet tests. This difference represents a compromise between signal loss and differentiation that can be tuned to the exact conditions of interest when the sensor is employed.

Correlation of peak outputs between custom and reference sensors for all over-pressurization tests was best approximated by a second-order polynomial equation (Fig. 4). After applying the complementary filter at the selected cutoff frequency, peak signal from the custom sensor had excellent correlation with the reference transducer for both bare sensor ($R^2 = 0.972$) and in-helmet ($R^2 = 0.987$)-mounting configurations. Signal impulse had good correlation ($R^2 = 0.927$) for bare sensor trials and excellent correlation ($R^2 = 0.964$) for in-helmet trials. Correlation of both peak and impulse outputs for blunt impact tests was also best approximated with a second-order polynomial equation. Excellent correlation existed between the two sensors with $R^2 = 0.998$ for peak signal and $R^2 = 0.996$ for signal impulse.

Time series data recorded by each sensor were in good agreement for bare sensor and in-helmet over-pressure, and excellent agreement for blunt impact test conditions. Mean cross-correlation values between custom and reference transducer time series data were 0.913 (SD 0.054; range 0.814–0.982), 0.902 (SD 0.045; range 0.837–0.957), and 0.957 (SD 0.004; range 0.952–0.960) for the respective conditions. Exemplar time history signals measured by both custom and reference transducers are provided in Fig. 5. The selected tests (trial 2 bare over-pressure at 103.4 kPa driver pressure; trial 3 in-helmet over-pressure at 792.9 kPa driver pressure; and trial 1 blunt impact at 15-cm drop height) have cross-correlation values (bare-sensor = 0.918, in-helmet = 0.915, blunt = 0.957) similar to the mean of all tests of their respective conditions, providing a visual example of the mean signal agreement.

DISCUSSION

Significant improvements in personnel- and vehicle-protective equipment have increased the survivability of soldiers in blast events that would have likely been fatal in the past. As a result, the frequency of bTBI, especially mTBI, injuries in soldiers returning from Iraq and Afghanistan has significantly increased.[11,12,21] A consequence of these injuries has been linked to several chronic problems, such as poor general health, persistent somatic post-injury symptomology, development of post-traumatic stress disorder (PTSD), and increased likelihood of depression.[11] These associations or relationships, however, are not unequivocal,[23] potentially indicating either a high variability in the effects of blast and/or an unclear link between the high complexity and variability of blast events and clinical outcomes. To better understand the etiology of blast injury, a method for characterizing the blast environment has been developed that can be potentially used in-theater to quantify true blast exposure in the field which can be related the primary, secondary, and tertiary effects of blast with clinical outcomes.

Existing solutions to measure blast effects in theater are costly, difficult to implement, encumbering, and do not provide sufficient characterization of the blast exposure to understand blast effects.[5] Helmet-mounted sensors currently deployed are rigidly mounted into existing ACH helmets and incorporate a single tri-axial accelerometer. A consequence of this mounting technique is the inability to differentiate helmet accelerations from head accelerations[13] which often results in measurement of helmet resonance rather than human exposure to blast. Also, by using only a single tri-axial accelerometer, the data are limited to acceleration at that point only and cannot be accurately translated to the whole head without additional information regarding the direction of impact and rotational kinematics present.[5,6,18] Moreover, currently deployed helmet-mounted sensors only provide quantified environmental blast severity and not human exposure to blast, which is necessary to elucidate the etiology of blast injuries associated with over-pressurization and/or blunt impacts. Because of these limitations, a flexible custom polypropylene electret custom sensor was created, which can simultaneously quantify both over-pressurization and blunt impacts and has the potential for in-helmet implementation without compromising fit, form, and function of the helmet when constructed into an optimized form factor.

Because military personnel may be required to carry a vast array of equipment, a primary aim of any personnel-borne device to record blast exposure should be to reduce system complexity and form-factor while maintaining the system's ability to measure the blast

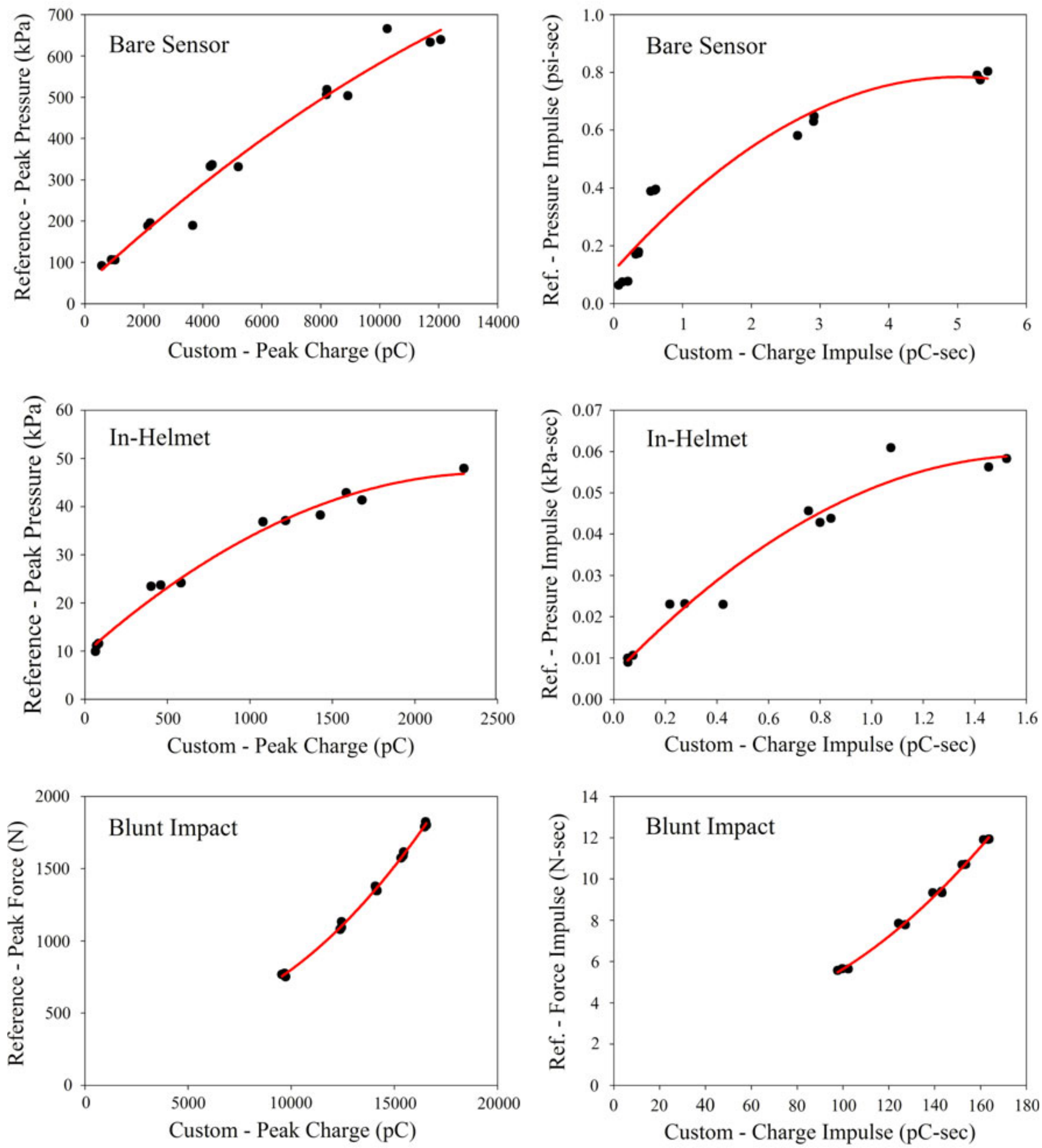

FIGURE 4. The relationship between peak and impulse signals measured by the custom and reference sensors was best approximated by a second-order polynomial curve. After being passed through the complimentary filter, custom sensor output had excellent correlation ($R^2 > 0.95$) with reference sensors for all conditions except signal impulse for bare sensor over-pressurization trials which had good correlation ($R^2 = 0.927$).

event accurately. Since over-pressurization and blunt impact events occur in different frequency domains, one option for reducing system complexity is to use a single sensing technology to measure both events and parse out the signal associated with each type of event using a complementary high-pass/low-pass filter. The differences in frequency domain can be easily seen by examining the pulse width of the reference sensor measures for each of the three conditions evaluated in this study (Fig. 5). Pulse width is typically defined as the temporal distance between the 50th percentile of peak amplitude on either side of a signal's primary peak.[17] Over-pressure trials had mean pulse widths of 9.3×10^{-5} s (SD 5.5×10^{-5}; range 5.2×10^{-5}–2.0×10^{-4} s) and 8.0×10^{-4} s (SD 3.3×10^{-4}; range 1.5×10^{-4}–1.2×10^{-3} s) for bare sensor and in-helmet

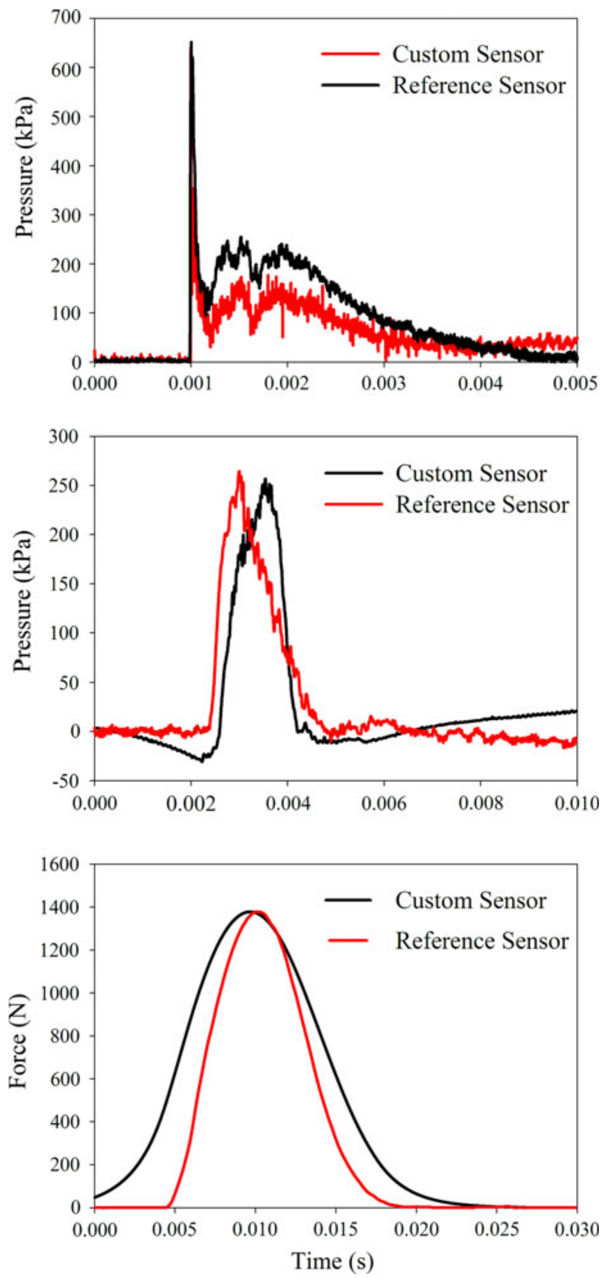

FIGURE 5. Exemplar trials for bare sensor over-pressurization (top), in-helmet over-pressurization (middle), and blunt impact (bottom) are shown. Custom sensor signals shown have been passed through the selected complementary filter to differentiate over-pressurization events from blunt impact events. Charge output from the custom transducer for all time points was scaled using the ratio of peak output between the custom and reference transducer. Cross-correlation values for these trials (0.918, 0.915, and 0.957, respectively) are most similar to the mean cross-correlation values of all trials by condition.

trials, respectively, while blunt impact events had an average pulse width of 6.8×10^{-3} s (SD 3.0×10^{-4}; range 6.4×10^{-3}–7.4×10^{-3} s). With a pulse width for bare sensor over-pressure being at least two orders of magnitude lower than blunt impact, and in-helmet over-pressure being one order of magnitude lower than blunt impact, an apparent gradient of frequencies exist between conditions allowing for fine-tuning of an optimum cutoff frequency depending on the signal of interest. For the tests conducted in this evaluation, we chose a cutoff frequency of 80 Hz to differentiate signals. This filter was applied to a broad set of evaluations, and was shown to be robust. While it is not clear how this specific cutoff frequency can be applied to in-theater conditions, we propose that these general methods, can be applied to measurements of differing signal characteristics, and, depending on the type of event of interest, be finely tuned to extract the appropriate signal.

To evaluate the performance of the custom sensor, we conducted a series of bench-top over-pressurization and blunt impact trials to compare the custom sensor with gold-standard laboratory reference sensors. A shock tube was employed to evaluate the custom sensor's over-pressurization measurement capabilities, and a linear drop tower was employed to characterize the sensor's performance during blunt impact conditions. Excellent agreement was found between the custom and reference peak and impulse measurements for over-pressure and blunt impact conditions. In addition, cross-correlation between signal time-history of the custom and reference sensors were good to excellent depending on event type and severity, suggesting that further signal feature extraction is possible if required for alternative applications. Regression analysis identified correlation between the custom and reference sensor's peak and impulse measures were best represented by a second-order polynomial for all conditions. The nonlinear relationship between the custom and reference sensor can be attributed to nonlinearity in the electret sensing material and the wide range of input conditions evaluated. The material has a nonlinear region relative to charge output at the initial time of deflection and/or compression compared to that of the primary deflection event. The sensor then begins to reach an asymptote as it reaches a point of maximum deformation. This nonlinearity can easily be observed through a cross-plot regression of a single trial (Fig. 6) where the nonlinear region occurs at lower charge output and becomes linear as output increases. Because of this, the bounds of the sensing range can, theoretically, be adjusted to a desired range using alternative packaging, and the nonlinearity does not have to inhibit the sensor performance as long as it is accounted for with calibration.

Several limitations of this study exist, which should be considered when interpreting the findings. First, while the range of peak pressure and force evaluated and the durations of those events are consistent with

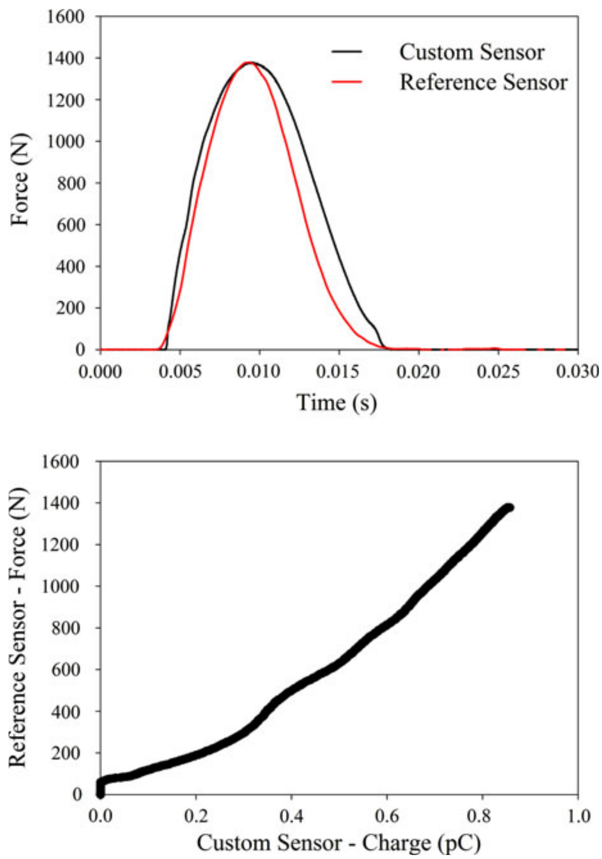

FIGURE 6. Nonlinearity between the custom and reference sensors can be explained by material hysteresis of the custom sensor. For comparison, the custom and reference sensor data shown (top) were filtered with a zero-lag low-pass Butterworth filter (order = 1; Fc = 10 kHz). A cross-plot regression between the start and maximum measured forces (bottom) of a single trial (trial 1, blunt impact, 15 cm) shows that the sensor is nonlinear in the initial phase of deflection/compression and becomes linear during the primary portion of the event.

those obtained from open-field blast reconstructions, the exact in-theater conditions are unknown. Further evaluation of both the sensing material and filtering methodology in a blast environment is required to ensure accuracy in complex environments, such as blasts events occurring in closed systems (e.g., in-building, in-vehicle, etc.), where multiple reflective waves may exist. For example, blunt impact due to projectile, which was not evaluated in this study, may result in frequencies that approach those of in-helmet over-pressure. In these circumstances, it may be necessary to augment the methods described in this study with additional differentiation techniques (e.g., temporal algorithms to take advantage of the anticipated timing difference between the over-pressurization wave and blunt impact, combination of in-helmet and external helmet sensors, etc.). In addition, evaluations consisting of combined blunt impact and over-pressure trials were not conducted. While this is a limitation, the likelihood of an in-theater event resulting in a soldier experiencing an over-pressure wave with simultaneous blunt impact is low considering that these events occur on the order of micro to milliseconds. Because of this, evaluating each event separately in the laboratory is most likely sufficient for initial characterization of the sensor. Finally, test results provided in this communication are for a single sensor coupon only. To equip an ACH helmet that can be borne in theater, the size and shape of the custom sensor will most likely require modification to optimize for performance (e.g., full head coverage, omnidirectional sensing, etc.). Because sensing area is dependent on these physical dimensions, the values for custom sensor peak and impulse signal will vary, and the values reported in this study are not directly applicable for field use. With this change in custom sensor output, however, we do not anticipate any effect on correlation with reference parameters.

Owing to the complexity of injuries sustained in theater from blast events and the unclear etiology of injuries associated with these events, the ability to measure in-theater blast exposure and distinguish the contribution of over-pressurization and blunt impacts is of great importance. With this validation study, we have shown that a custom sensor created from flexible electret film can be employed to accurately measure both over-pressure and blunt impact events. In addition, a single sensor can be utilized to capture both types of events by filtering the recorded data into the distinct frequency domain of each event type simplifying integration into existing helmets. When coupled with clinical outcome measures, direct measurements of trauma-producing blast exposure can add to our knowledge base of bTBI which may lead to improvements in protective equipment and potentially the creation of sensitive and specific thresholds for injury detection.

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CONFLICT OF INTEREST

Jeffrey J. Chu, Richard M. Greenwald and Simbex have a financial interest in the materials and methods developed within this study.

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