Data Filtering for the Analysis of Biological Tests for Behind Armor Blunt Trauma Studies

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Abstract. The use of body armor has been shown to reduce the risk of penetrating injuries among military personnel. While the body armor reduces the risk of penetrating injuries, the energy from the impact can still be transferred through the armor, causing backface deformation, resulting in injuries to the underlying tissue. The resistance of the ballistic armor is tested based on the maximum allowable backface deformation limit of 44 millimeter(mm). The standard was developed over four decades ago for soft body armor from a limited set of data from goat experiments. Although the standard was developed for soft body armor, the standard was adopted for hard armor. The 44mm standard is independent of threat level, threat type, and impact location. The development of thoracoabdominal region specific injury criteria will aid in assessing and designing body armor and improve BABT safety against current and future threats. Surrogate models can be used to develop these region injury risk curves for BABT application. Cadaver swine and human models have been used in automotive studies for over 60 years for developing injury criteria. Although, automotive risk curves are not appropriate for BABT application due to lower velocity loading conditions and greater impacting mass, the hybrid approach of utilizing swine and human cadavers to develop scaling relationships can be used to develop region specific risk curves for BABT. These tests will require data collection on biological specimens at high rates. Although there are established standards for processing these data in the automotive environment, there are no established standards or consensus for processing data from BABT experiments. This study analyzed indentor accelerometer data collected from swine and human cadavers and developed a protocol for data processing to determine load applied to thoracoabdominal body regions for BABT applications.

1. INTRODUCTION

The use of body armor has become increasingly prevalent in military and law enforcement contexts, with the aim of protecting individuals from ballistic threats [1]. However, the use of body armor can also result in a phenomenon known as behind armor blunt trauma (BABT), which occurs when an individual is struck by a projectile that is unable to penetrate the armor but still causes injury. BABT can result in a range of injuries, including fractures, contusions, and internal organ damage [2]. Despite the potential severity of BABT injuries, there is a lack of comprehensive data on the incidence and nature of these injuries in peer-reviewed literature, like the automotive field. This lack of data makes it difficult to develop effective measures to mitigate the risk of BABT and improve body armor design.

The National Institute of Justice (NIJ) Standard-0101.06 is an armor test standard commonly used in the industry as a benchmark for evaluating the ability of body armor to protect against BABT [3]. Tests are conducted by placing the body armor over Roma Plastilina No. 1 (RP1) clay backing and targeted based on the prescribed conditions in the standard. Assuming there is no penetration of the armor, the armor is solely evaluated based on the maximum allowable backface deformation limit of 44 mm. It is important to note that the 44 mm limit was developed specifically for soft body armor based on a limited set of experiments on live goats [4]. The original researchers of the study underscored its limitations and emphasized the need to conduct additional tests that included animal experimentation and simulants to improve the 44 mm clay standard. The legacy standard developed over four decades ago remains the current BABT standard independent of armor type, threat level, or impact location on thoracoabdominal region covered by armor.

Biomechanical responses of the human tissue, anatomy, and loading conditions from back-face deformation play a significant role in resulting injury and the injury mechanism. In humans, the different mechanical properties of musculoskeletal structures in the thoracoabdominal region (tissues, organs, and ribcage), may lead to different responses in injury, injury tolerance and mechanisms [5]–[8]. It is important to delineate these region-based tolerances considering a single threshold of 44 mm limit may not be appropriate in determining injury risk severity. Additional testing is needed to develop risk curves for different thoracoabdominal regions. An hybrid model of cadaver and live swine tests in conjunction

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with human cadavers have been used to develop injury risk criteria for automotive safety for decades [9]. Although these risk criteria exist, they are not applicable for BABT injures as the impact velocities are significantly greater and mass of projectile is lower compared to velocities and masses used for automotive testing. Additional testing is needed to develop region specific injury risk curves for BABT by utilizing cadaveric swine, live swine, and human cadavers, similar to automotive safety testing, to update the legacy 44 mm standard.

These experiments will require the use of sensors such as accelerometers to capture the loading event at high rates. Existing standards for processing injury biomechanics data signals are based on automotive loading cases associated with lower velocities than those seen in military environments. The objective of this study was to process data from behind armor blunt trauma (BABT) experiments on post-mortem human subjects (PMHS) and swine cadavers at varied frequencies to standardize the filtering system for use in the development of BABT injury criteria.

2. METHODS

All experiments were conducted in compliance with the Institutional Animal Care and Use Committees at all three academic institutions of the authors: Duke University, University of Virginia, Medical College of Wisconsin, and Zablocki Veterans' Administration Medical Center. Prior approval was obtained from the Animal Care and Use Review Office (ACURO) of the U. S. Department of Defense.

2.1 Impactor Design

High-speed flash x-ray images were used to determine the depth and diameter of backface deformation in hard body armor (UHMWPE) from rifle rounds (7.62-mm NATO ball round) [10]. An impactor approximately 100 mm in diameter with a dome depth of 25mm was designed based on measurements from flash x-rays (Figure 72). A triaxial accelerometer (Endevco) was mounted within the impactor using a hardwired (DTS Slice Nano) or 'onboard' (DTS Slice Pro) data acquisition system and sampled at over 100 kilohertz (kHz). (Figure 73)

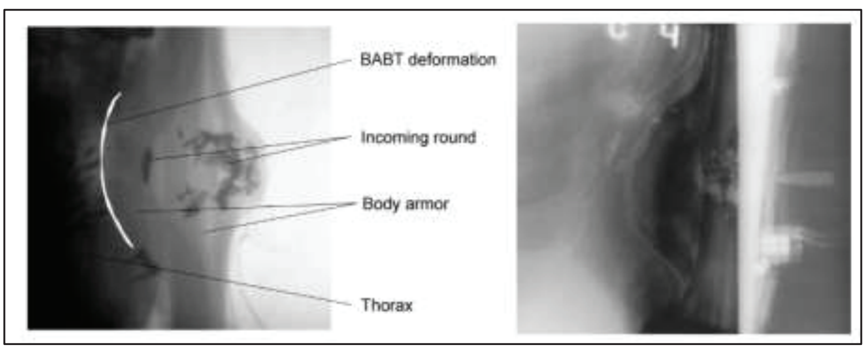

Figure 72: Backface deformation profile from rifle round in hard body armor [10]

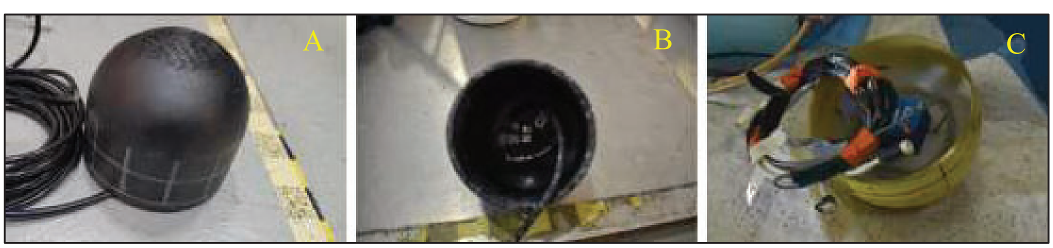

Figure 73: (A-B) Wired indentor with triaxial accelerometer. (C) Wireless indentor with triaxial accelerometer with on-bord data acquisition system

2.2 Experimental Setup

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A gas-driven launching system was used to propel the indentor to the target at varying velocities. The indentor was loaded into an open-ended tube and pressurized gas was released behind the indentor propelling it towards the indented target at the exit of the tube. Human cadavers and swine cadavers were strapped to a custom harness and hoisted up using a winch such that they were positioned upright in front of the tube (Figure 3).

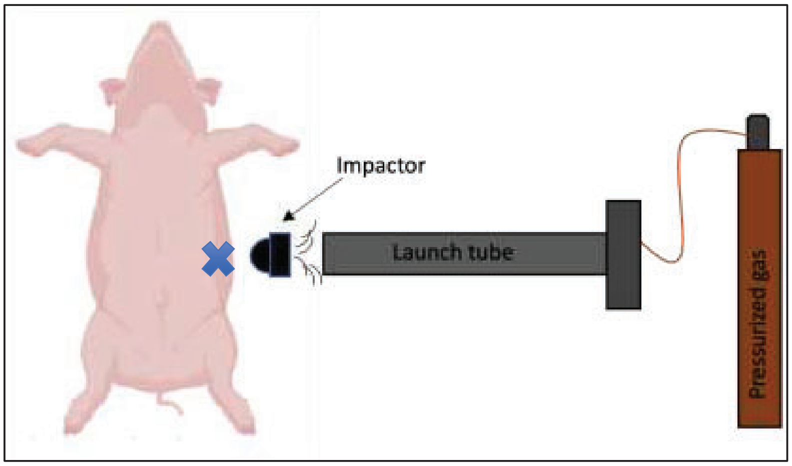

Figure 74: Experimental setup with swine position at the exit of launch tube

This impactor was used to impact multiple thoracic regions: heart, lungs, kidney, liver, sternum, and spine. The specimen position was adjusted based on the targeted location. Impacts simulated 7.62x51 NATO bullets at velocities of 311-1067 (meters/second) m/s.

2.3 Data Processing

Data from the indentor were processed with a four-pole Butterworth filter at 1, 2, 4, and 10 kHz. Power spectrum density functions for all signals and impacts were analyzed using log and natural ordinate scales. Similar experiments were conducted at the three institutions of the authors of this study with swine cadavers and human cadavers to add to the feasibility of using the simulated indentor on different surrogates and at different thoracoabdominal regions. Although other institutions used similar experimental setups, some variations existed in launching systems, acquisition systems, accelerometers, and indentors within institutions. Data from all institutions were also processed and analyzed for the present study.

3. RESULTS

Over 100 acceleration signals from the indentor impacts to targeted locations in swine and human cadavers were analyzed. Signals were examined to determine the applied load to the surrogates, focusing on the impacting event window. Small subset of impact tests were removed from the dataset due to low quality signals, dead channels, or broken cables.

Raw and filtered signal, and Power Spectral Density (PSD) of indentor accelerometer from a single swine (Section 3.1) and human (Section 3.2) cadaver tests are shown as an example of signal examination process undertaken to identify a low-pass filter appropriate for processing biomechanical signals in BABT experiments. PSD results are presented in form of two different plots, linear and log scales, for sake of clarity for the reader.

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3.1 Swine cadaver results from institution 1

Impactor acceleration data from left lung impact to a swine cadaver are presented in **Error! Reference source not found.** and Figure 76.

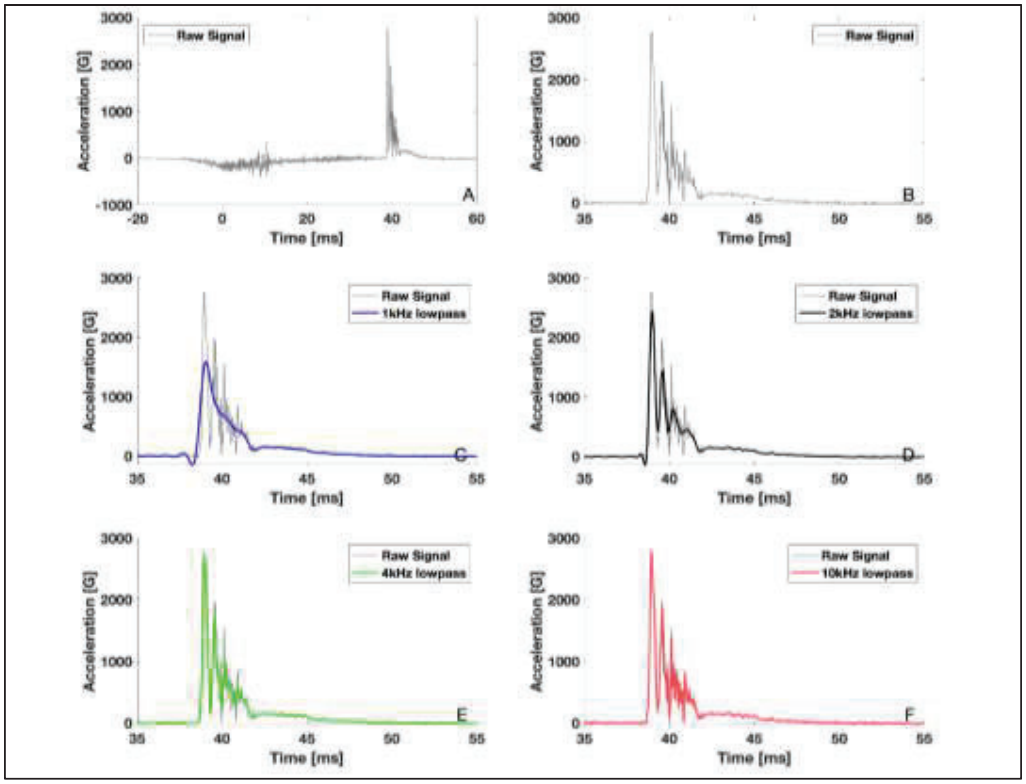

Figure 75: Raw signal (A) of indentor loading event (B) from impact to left lung on swine cadaver is filtered at 1 kHz (C), 2 kHz (D), 4 kHz (E) and 10 kHz (F)

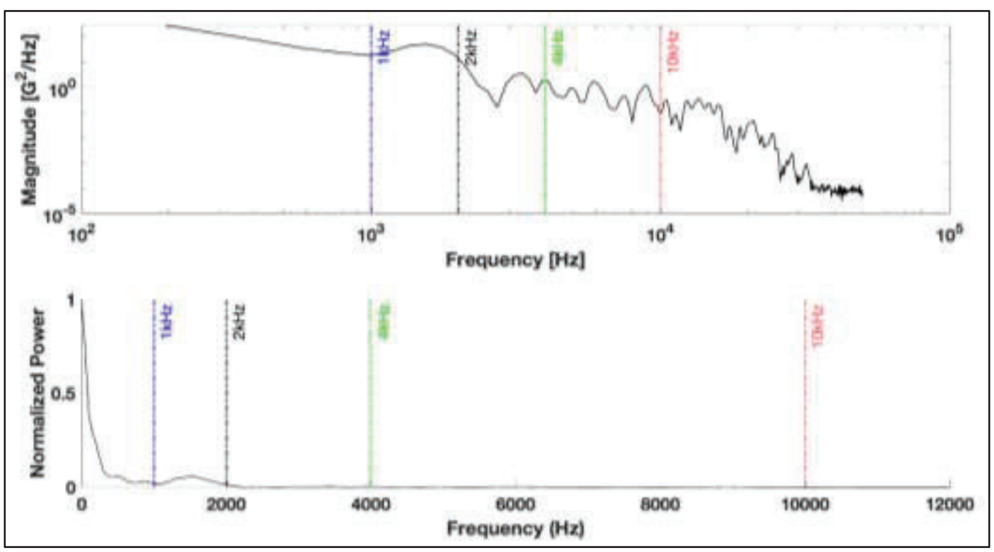

Figure 76: Power spectral density plots in log (top) and linear (bottom) scale for indentor acceleration signal from impact to left lung on swine cadaver

3.2 Human cadaver results from institution #1

Impactor acceleration data from spine impact to a human cadaver are presented in Figure 77 and Figure 78.

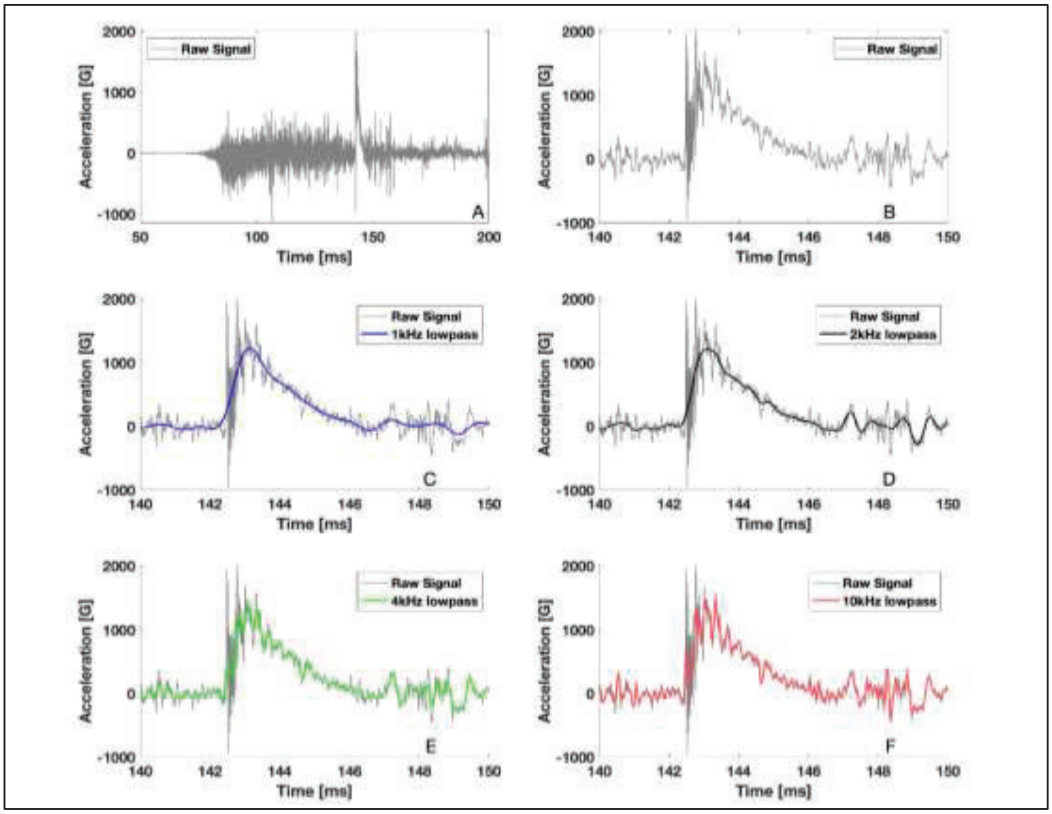

Figure 77: Raw signal (A) of indentor loading event (B) from impact to spine on PMHS is filtered at 1 kHz (C), 2 kHz (D), 4 kHz (E) and 10 kHz (F)

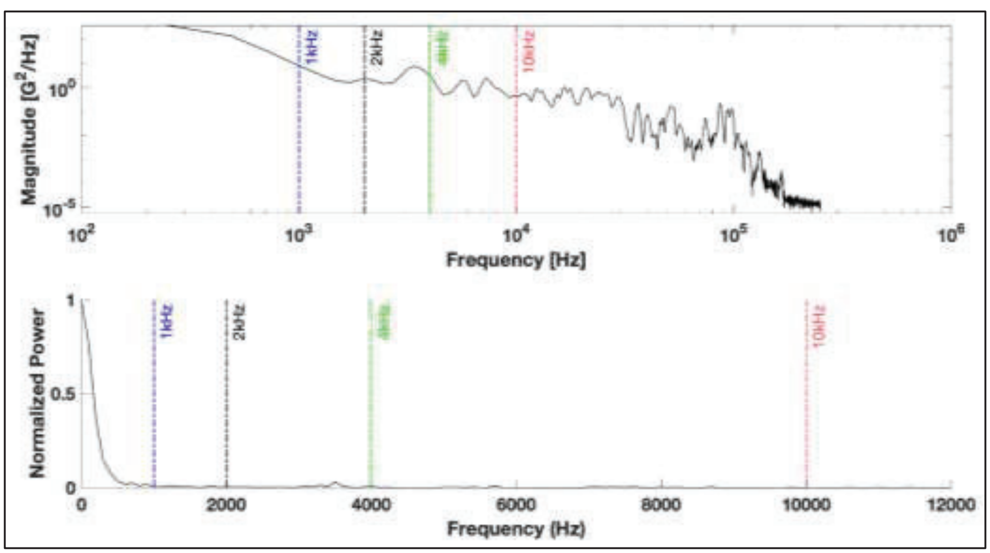

Figure 78: Power spectral density plots in log (top) and linear (bottom) scale for indentor acceleration signal from impact to spine on PMHS

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3.3 Results from other Institutions

Similar analysis was conducted on impactor data from other two institutions of authors of this study. Impactor acceleration data from liver impact to a human cadaver are presented in Figure 79 and Figure 80 from institution #2 and data from left lung impact on swine cadaver are presented in Figure 81Figure 82 from institution #3.

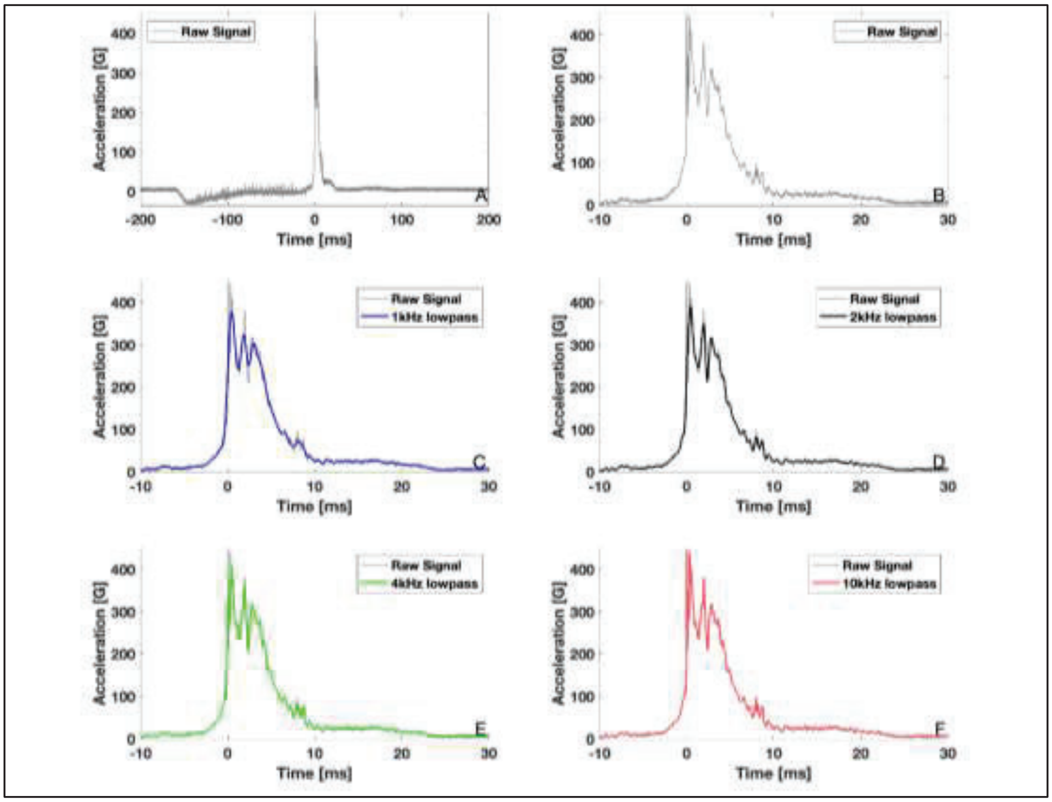

Figure 79: Institution # 2 raw signal (A) of indentor loading event (B) from impact to liver on PMHS is filtered at 1 kHz (C), 2 kHz (D), 4 kHz (E) and 10 kHz (F)

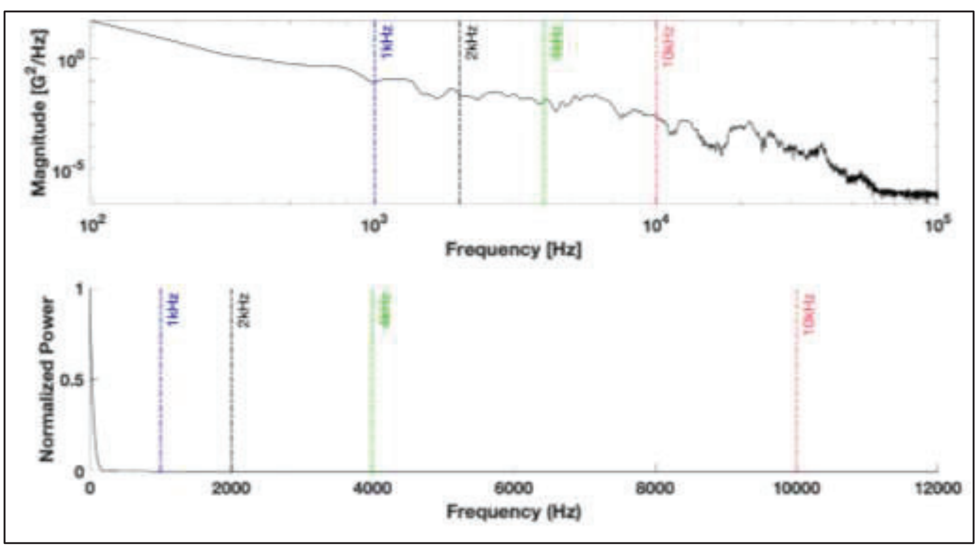

Figure 80: Power spectral density plots in log (top) and linear (bottom) scale for indentor acceleration signal from institution #2 from impact to liver on PMHS

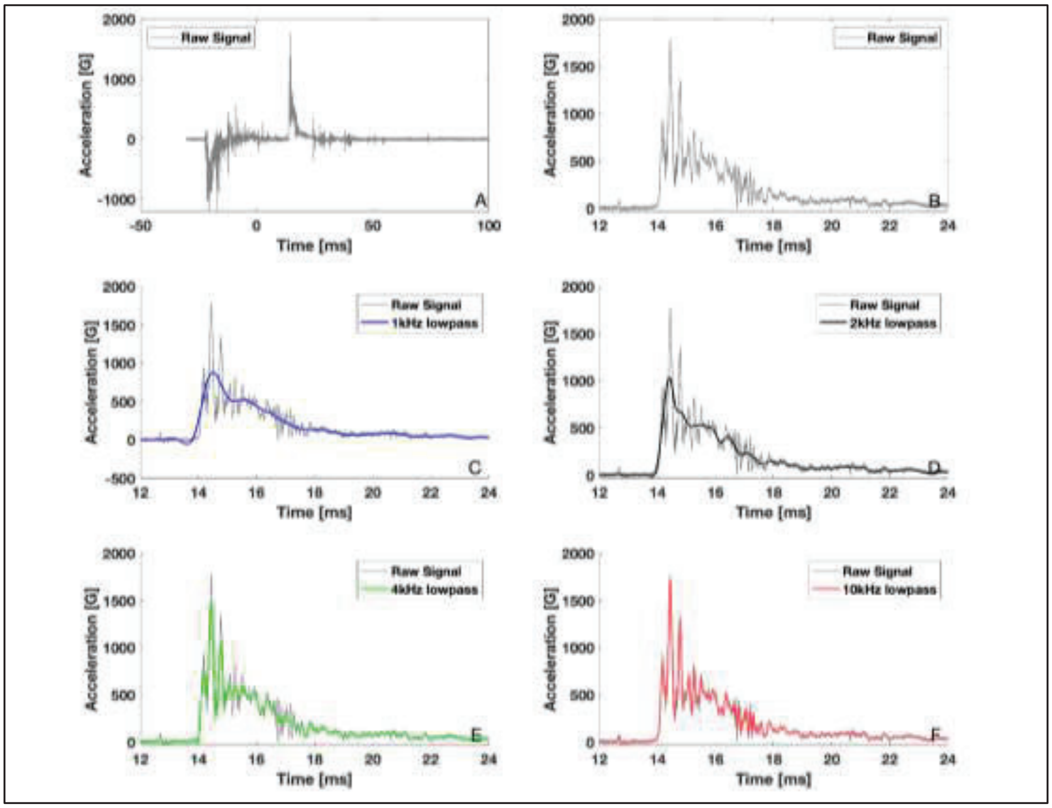

Figure 81: Institution # 3 raw signal (A) of indentor loading event (B) from impact to left lung on swine cadaver is filtered at 1 kHz (C), 2 kHz (D), 4 kHz (E) and 10 kHz (F)

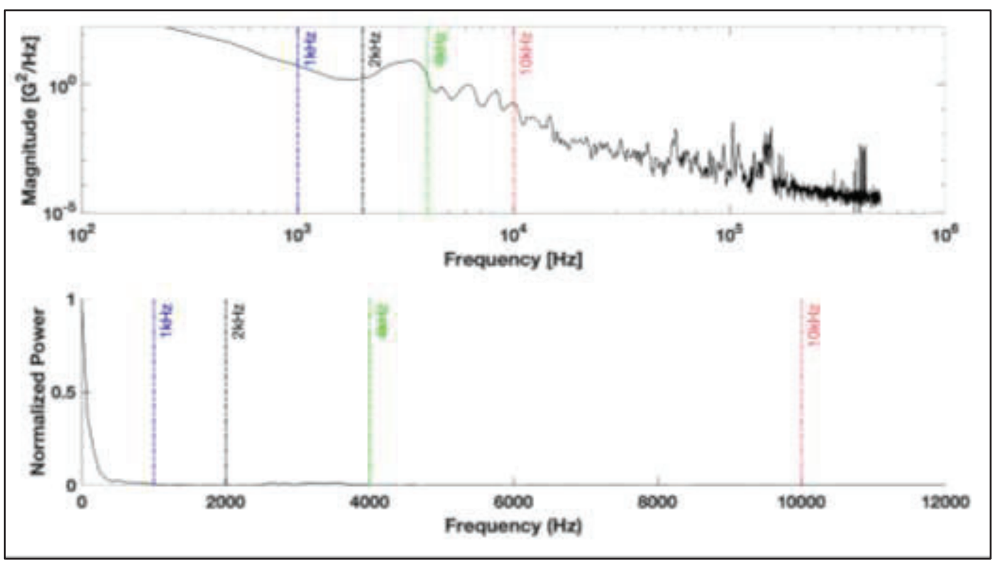

Figure 82: Power spectral density plots in log (top) and linear (bottom) scale for indentor acceleration signal from institution #3 from impact to left lung on swine cadaver

For each body region from human and swine cadavers, temporal analysis of raw and processed signals were processed at each frequency. For all body regions, in addition to the actual loading profile, raw data briefly included Gaussian noise. Filtering the signal at 10 kHz significantly reduced the noise with a concomitant peak amplitude decrease while the signal remained oscillatory under varying loading conditions. Filtering at 4kHz further decreased the amplitude and reduced the oscillatory nature for a

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subset of data. This phenomenon was primarily observed for impacts at lower velocity (<40 m/s) impacts to lungs. While oscillations were minimal at 2kHz, the 1kHz filter produced the smoothest single wave-type pulse without any oscillatory pattern.

4. DISCUSSION

Data acquisition and processing of signals is an important component of data analysis in any dynamic loading experiment. Researchers in the automotive field including academia and industry have dealt with this critical issue for years. The Society of Automotive Engineers (SAE) assembled groups to decide the best approaches and developed standards (SAE-J211) [11]. Impacts tests conducted with sled equipment that delivers dynamic loading to biological surrogates (human cadavers in particular), pendulum that delivers localized impacts (animals and human cadavers and physical models such as the Hybrid III manikin), drop tests that applies loading similar to sled equipment (whole body and isolated component human cadavers and manikin), and other loading methods continue to use the SAE standard as the accepted procedure for signal processing and filtering. For example, sled accelerations are filtered using channel filter class CFC 60, acceleration on the head and thorax on both biological surrogates and physical models are filtered at CFC 1000, and pendulum impactor accelerations are filtered at CFC 1000 [9], [12]–[14]. Similar widely accepted international procedure for BABT impacts does not exist to the best knowledge of the authors of this study [15]. Some impact loading studies with human cadavers and manikins have used the same automotive filtering techniques. As an example, a brief review of BABT-related papers presented at the recent PASS conferences confirms the lack of consensus, and in addition, unlike automotive studies, not all BABT studies have reported filtering methods [16]–[20] . While both automotive and BABT studies apply to the load dynamically via impact to different regions of the human body, the loading magnitudes are greater in the BABT scenario. Consequently, a method to process signals for BABT applications is needed. The present study was designed with this intent, and as a first step, used experiments with a biological model as the overall aim of the project was to develop thoraco-abdominal injury criteria for different regions of live and cadaver-based human surrogates. Gathered accelerometer data from the indentor that applied the impact load to the swine and cadavers was used in the filtering analysis.

The results from the present study show that the 10 kHz filtered signals remove the Gaussian noise only to a certain extent, while decreasing the filter frequency had a larger effect; however, as expected, the peak amplitudes were lower with increasing filter frequencies. Filtering at 1 kHz produced the smoothest curve in all cases, and from all tests at the three institutions. But the peaks reduced considerably. It should be noted that acceleration signals depend on the region of impact: skeletal regions tend to produce sharper and higher rise time profiles that add to the noise while impacts to softer regions (e.g., unprotected liver) tend to spread the pulse with lower peak acceleration and less Gaussian noise. Flesh thickness is also a modulating factor. A common finding from these varied tests at three institutions is that beyond 2 kHz, the power spectral density plots show little to no signal for BABT loading event and hence, this filter can be considered as a true representation of impact responses with live and cadaver biological surrogates, and at the 2 kHz will also not considerably compromise the peak amplitudes of the acceleration signal. This frequency is also reasonable considering the fact that this is twice the filter rate used in automotive studies. A similar signal processing analysis with BABT impact has not been published to the best knowledge of the authors. While preliminary, the authors are analyzing more signals from additional tests to the three surrogates to reinforce these findings.

The advantage of filtering the collected signals that are at higher sampling rates (automotive pulses are longer and sampling frequencies of 20 kHz are acceptable, in general) is to enable post processing for secondary variables can be made with confidence. For example, it is customary to remove inertial effects of the indentor by attaching an accelerometer to the indentor to calculate the actual forces to the biological or physical model. Likewise, once the acceleration signals are filtered, parameters such as the velocity of the indentor that applied the loading to the surrogate, and compression imparted to the surrogate can be calculated by integrating the filtered accelerometer signal. As stated earlier, in automotive studies have used filtered accelerometer signals to determine deflection on human surrogates and developed injury criteria [21]. As-collected raw signals from the impact test cannot be used for this purpose. Once velocity and compression/deflection are obtained, other measures such as viscous criteria ($[VC]_{max}$, V_{max} C_{max}) and momentum transferred to the surrogate, can be obtained [22], [23]. All these measures are potential candidates for BABT injury criteria. Optical methods can be used in lieu of the indentor accelerometer-derived measures; however, they have issues such as visibility to gather data and difficulty in obtaining off-axis components, and frame rate is also an issue as greater impact velocities require greater frame rates that may involve camera resolution/pixel constraints. In addition, camera placements to capture unobstructed images throughout the experiment can be challenging, especially with biological surrogates. Live animal experiments add to this complexity as often other physiological monitoring equipment also require space in the laboratory with clinician involvement. These factors affect the accuracy of optical measurements. As sensors signals can be captured at very high frequencies, they are suitable to BABT applications, and the approach used in the present paper would serve as a first step in the process of developing a well-defined and accepted filtering algorithm.

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