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Review of Post-Mortem Human Subject Thoracic Response of Blunt Non-Penetrating Ballistic Impact to Determine Surrogate Biofidelity Requirements

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14. ABSTRACT

When body armor successfully defeats a ballistic threat, the underlying surface experiences a dynamic deformation which creates a blunt insult to the wearer. Energy transmitted from the armor's local backface deformation (BFD) to the wearer can produce high loading rates with sufficient deformation to produce trauma to the underlying soft tissues and skeletal structures. Resulting BFD injuries are region-specific because of the anatomical structures in different areas of the thorax, thus selected surrogates may require varied material properties to properly mimic the diverse responses. Current test standards use Roma Plastilina #1 (RP1) clay to measure impact severity by indentation (Bolduc & Anctil, 2010; Shewchenko et al., 2020); however, the current standards are inadequate due to the homogeneous material used and their inability to assess injury to the thorax. Researchers at the U.S. Army Aeromedical Research Laboratory have highlighted the need for better thoracic biofidelity in ballistic scenarios because current models, while more sophisticated, still struggle to accurately replicate complex human responses in military scenarios.

15. SUBJECT TERMS

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14. Abstract (continued)

This report provides a review of published research in open literature describing the physical surrogates used to study behind armor blunt trauma (BABT) resulting from blunt ballistic impacts to the thoracic region with a focus on studies that developed biomechanical response corridors derived from post-mortem human subject data. Despite advancements, current surrogates often fall short in replicating the complex dynamic responses of human tissues, and the lack of standardized biofidelity metrics and testing protocols hinders comparison and reliability across studies. Additionally, establishing post-mortem human subject biofidelity corridors for regions beyond the thorax, such as the abdominal area, is crucial for developing a fully biofidelic surrogate. By advancing the development of highly biofidelic thoracic surrogates, researchers can enhance the testing and evaluation of protective equipment (such as body armor), deepen their understanding of thoracic injury mechanisms, and develop more effective strategies for preventing and mitigating ballistic injuries, ultimately contributing to improved safety and health outcomes in military and civilian contexts.

Executive Summary

When body armor successfully defeats a ballistic threat, the underlying surface experiences a dynamic deformation that can create a blunt insult to the wearer. Energy transmitted from the armor's local backface deformation (BFD) to the wearer can produce high loading rates with sufficient deformation to produce trauma to the underlying soft tissues and skeletal structures. Resulting BFD injuries are region-specific because of the anatomical structures in different areas of the thorax, thus selected surrogates may require varied material properties to properly mimic the diverse responses. Current test standards use Roma Plastilina #1 (RP1) clay to measure impact severity by indentation (Bolduc & Anctil, 2010; Shewchenko et al., 2020); however, the current standards are inadequate due to the homogeneous material used and their inability to assess injury to the thorax. Researchers at the U.S. Army Aeromedical Research Laboratory (USAARL) have highlighted the need for better thoracic biofidelity in ballistic scenarios because current models, while more sophisticated, still struggle to accurately replicate complex human responses in military scenarios. This report provides a review of research published in the open literature describing the physical surrogates used to study behind armor blunt trauma (BABT) resulting from blunt ballistic impacts to the thoracic region with a focus on studies that developed biomechanical response corridors derived from post-mortem human subject (PMHS) data. Despite advancements, current surrogates often fall short in replicating the complex dynamic responses of human tissues, and the lack of standardized biofidelity metrics and testing protocols hinders comparison and reliability across studies. Additionally, establishing PMHS biofidelity corridors for regions beyond the thorax, such as the abdominal area, is needed to develop a fully biofidelic surrogate. By advancing the development of highly biofidelic thoracic surrogates, researchers can improve the testing and evaluation of protective equipment (such as body armor), deepen their understanding of thoracic injury mechanisms, and develop more effective strategies for preventing and mitigating ballistic injuries, ultimately contributing to improved safety and health outcomes in military and civilian contexts.

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Introduction

When modern body armor successfully defeats a ballistic threat, the underlying surface of the armor experiences a dynamic deformation that can create a blunt insult to the wearer. The armor deforms and fragments the impactor, dissipating the impactor's momentum by deforming the armor. However, energy transmitted from the armor's local backface deformation (BFD) to the wearer can produce high loading rates with sufficient deformation to produce trauma to the underlying soft tissues and skeletal structures. Research has shown that BFD into the thorax is sufficient to cause local and distant fractures, contusions, and hemorrhage as demonstrated in numerous animal studies (Clare et al., 1975; Cooper et al., 1982; Lidén et al., 1988; Mayorga et al., 2010; Prather et al., 1977; Sarron et al., 2000; Suneson et al., 1987). Resulting BFD injuries are region-specific because of the underlying anatomical structures in different areas of the thorax, thus selected surrogates may require varied materiel properties to properly mimic the diverse responses. When the response of the surrogate for the specified body regions falls within a defined corridor of post-mortem human subjects (PMHS) or living human responses, the surrogate is considered "biofidelic." Biofidelity of a surrogate must be assessed for different body regions exposed to specific loading conditions.

Test standards for assessing BFD use Roma Plastilina #1 (RP1) clay to measure impact severity by indentation (Bolduc & Anctil, 2010; Shewchenko et al., 2020). However, these standards have limitations, such as only supporting deformation measures while lacking other advanced engineering metrics (e.g., velocity, energy, force, strain). Standard development occurred from the 1970s through the 1980s using the scientific methods and knowledge available at the time (Prather et al., 1977; Lidén et al., 1988) when they established the deformation limit of 44 millimeters (mm). Unprotected and soft body armor-protected lateral thorax impact tests on goats were conducted to develop probabilistic models used to predict the likelihood of injury, known as injury risk curves (IRCs) (Prather et al., 1977). The developed IRCs were used to develop the clay indentation standard by matching goat tests with responses from alternative surrogates. The RP1 clay was selected as it suitably matched the biofidelity of the goat thorax responses and did not require other engineering instruments for evaluation. Since the development of the clay criterion 50 years ago, and despite national and international research efforts to improve the standard, the 44 mm limit is still widely used during the design, development, and injury assessment of soft and hard body armor (Carton & Khoe, 2020; Hanlon & Gillich, 2012; Lehowicz et al., 2012). In addition, the 44 mm limit is applied equally across the human thoracoabdominal regions covered by the body armor despite the varying injury tolerances in the different regions (Rafaels et al., 2018). Although this method has provided a level of protection, clay's homogeneous nature does not adequately represent the effects of non-penetrating blunt ballistic impact on the human body, raising concerns about its relevance in assessing injury potential and highlighting the need for alternative behind armor blunt trauma (BABT) surrogates with improved instrumentation.

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The history of anthropomorphic test device (ATD) development for the military is closely tied to ATD advancements in the automotive field; however, the biofidelity of most ATDs has not been established for the military environment. Studies by the automotive industry using ATDs led to improvements in vehicle safety for over 50 years. The National Highway Traffic Safety Administration (NHTSA) began vehicle crash testing in 1975 to evaluate vehicle safety performance. The first ATD used by the domestic automobile industry, Sierra Sam (Sierra Engineering Co., Tollhouse, CA), was a 95th percentile male ATD developed in 1949 for ejection seat testing by the U.S. Air Force, but this ATD lacked the biofidelity needed for comprehensive safety assessments (Mertz, 2002). Subsequent developments, such as the Hybrid II (HII) and Hybrid III (HIII) series ATDs by General Motors (Detroit, MI), improved the biofidelity of the ATDs by mimicking human physical characteristics and incorporating transducers to measure accelerations, deformations, and loading during collisions (Polanco & Littel, 2011). However, limitations persisted, particularly with the HIII surrogate, which demonstrated reduced biofidelity in areas like the thorax and abdomen (Watkins et al., 2022). While the Test Device for Human Occupant Restraint (THOR) (Humanetics, Farmington Hills, MI) demonstrates improved biofidelity compared to the HIII, particularly in its closer alignment with PMHS responses in frontal crashes (Watkins et al., 2022), it suffers from drawbacks in reproducibility and reliability, specifically in the thorax (Hikada et al., 2017). Despite being more biofidelic overall, THOR exhibits inconsistencies during thoracic testing when compared to the HIII, showing less reliable responses. Furthermore, although designed for enhanced biofidelity, THOR still displays deviations from PMHS responses in specific areas, notably exhibiting a stiffer abdomen and softer thorax (Martínez et al., 2003). Despite the advancements, ATDs like the HIII and THOR remain limited by engineering and practical constraints, underscoring the need for ongoing research and development to enhance their biofidelity, especially for military applications.

Most ATDs employed by the civilian automotive industry for assessing injury risk have not been evaluated for loading scenarios unique to the military environment (e.g., underbody blast, vertical impact, weapon recoil, non-penetrating ballistic impact) (Rhodes et al., 2022). To assess injury risk, researchers generate injury assessment reference values (IARVs) by comparing injury risk curves (IRCs) derived from PMHS tests to those of matched-pair ATD tests (Rhodes & McEntire, 2025). The ATD performance criteria developed by the automotive industry through this process were for specific ATDs and dynamic environments involving high-mass, low-speed impacts, namely civilian vehicle crashes. These performance criteria do not apply to non-penetrating blunt ballistic impacts; therefore, Department of Transportation (DOT)-approved IARV may not be appropriate for use in studying impacts that are substantially different from the ATDs' intended purposes (Rhodes et al., 2022).

For non-penetrating blunt ballistic impact research, a different approach to modeling and understanding injury mechanisms is required because of the differences in the mass, speed, and surface area of the impactors used for testing. The sensors and the internal design of the thorax within the HIII do not provide the kind of repeatable responses needed for measuring these impacts (Bir, 2000). Characterizing the biofidelity of ATDs is crucial for accurately assessing injury risk. The current state of ATD thoracic biofidelity is inadequate, particularly for military applications, because of the limited number of publicly available PMHS experiments that have been conducted to study global thoracic chest wall motion (Bass et al., 2006; Bir et al., 2004; Bir, 2000; Laurel & Eugene, 2018; Prat et al., 2012; Yoganandan et al., 1993). The human body response to non-penetrating ballistic impacts differs in force and deflection from previously established responses for automotive impacts (Kroell et al., 1971; Kroell et al., 1974) and the behavior of numerical models dedicated to automotive impacts is unsuitable for non-penetrating blunt ballistic impacts (Thota et al., 2014a, 2014b). Bir et al. (2004) illustrated the differences between the impactor masses and velocities used for non-penetrating blunt ballistic impact tests versus those used in automotive industry tests (Figure 1). The velocities and masses used to simulate automotive impacts ranged from 4 to 15 meters per second (m/s) and masses ranged from 5,000 to 35,000 grams (g); however, to simulate non-penetrating blunt ballistic impacts, researchers used low-mass, high-velocity impactors with impact velocities that ranged from 20 to 250 m/s and masses that ranged from 20 to 200 g.

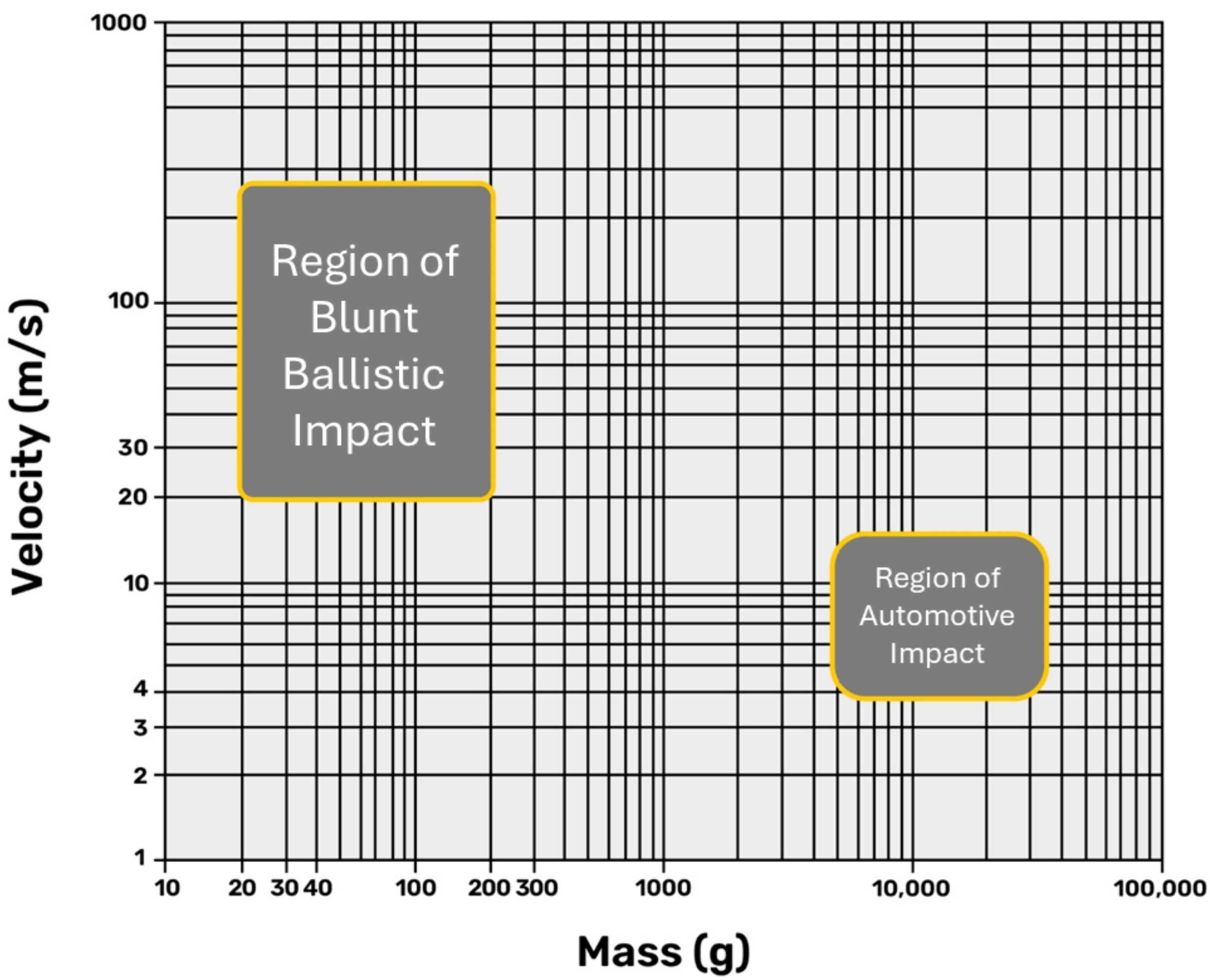

Figure 1. Regions of blunt impact testing are shown as a function of impactor impact velocity versus mass. The region of blunt ballistic impacts (low-mass, high-velocity) involves impact velocities of 20 to 250 m/s and masses of 20 to 200 g. Figure modified from Bir et al. (2004).

Thoracic biofidelity is needed to validate ATDs or other surrogates, specifically for non-penetrating blunt ballistic impacts, so that the researchers can better assess, predict, and mitigate injury risks in military environments. This review of past research is intended to provide an overview of the highlighted studies that developed biomechanical response corridors derived from PMHS data and testing methodologies used to study BABT resulting from non-penetrating blunt ballistic impacts to the thoracic region.

Methods

A comprehensive literature review was conducted to identify pertinent thoracic biofidelity research in the context of non-penetrating ballistic impacts. The U.S. Army Aeromedical Research Laboratory (USAARL) researchers conducted a multi-stage search across three databases: PubMed, SAE International (SAE), and Google Scholar. The first PubMed search used the keywords ("biofidelity") AND ("anthropomorphic test device"). PubMed was queried again using keywords including ("models" OR "physiopathology" OR "etiology") AND ("biological" OR "thoracic injuries" OR "wounds" OR "nonpenetrating wounds"). The final PubMed search used the keywords ("biofidelity") AND ("ballistic"). The SAE search used the keywords "biofidelity," "thorax," and "anthropomorphic test device." The first Google Scholar search used the keywords "blunt ballistic thoracic response corridors." Another Google Scholar search used the keywords "thorax back face deformation." A final search was conducted on Google Scholar with keywords "human thorax biofidelity corridors." This multi-stage, iterative search strategy enabled two USAARL researchers to review the resulting literature to identify the most relevant studies for thoracic biofidelity of non-penetrating ballistic impacts. For each article reviewed, the following parameters were extracted and analyzed: impactor type, mass, velocity, and diameter; impact location; and applicability of biofidelity corridors. The impactor masses and impact velocities of Bir (2000) and Bir et al. (2004) were noted for comparison to additional literature to determine if the exposure was applicable to high-velocity impactors. Studies that developed applicable biofidelity corridors were identified and the corridors were digitized for comparison to Bir et al. (2004) along with the testing parameters used to execute the testing. If surrogates were used, limitations were noted.

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Results

The PubMed search yielded 77 results, of which only Bass et al. (2006) was relevant and was selected to be reviewed. The second PubMed search yielded 572 results, but none were relevant to the specific topic. The final search in PubMed identified the Chaufer et al. (2024a) article titled "Review of non-penetrating ballistic testing techniques for protection assessment: From biological data to numerical and physical surrogates," which was used to explore the references for additional articles. This publication referenced Bir (2000), Bir et al. (2004), Bolduc & Anctil (2010), Bass et al. (2006), Roberts et al. (2007), Yan et al. (2020), and Sedberry & Foley (2019), all of which were selected for this review. The SAE search yielded 20 results; however, none were relevant and therefore not used in this review. The first Google Scholar search yielded 3,950 results. Upon review of the first five pages of results, the authors selected Bir & Eck (2005) for review. The second Google Scholar search yielded 20,200 results; however, upon review of the first five pages of results, only two articles were selected for this review (Jenerowicz et al., 2023; Shewchenko et al., 2020). Shewchenko et al. (2020) referenced Dau (2012) and Bir & Eck (2005) which were relevant to this review and therefore selected. The final Google Scholar search identified Chaufer et al. (2024b), another key article reviewed in this paper. Through this iterative and targeted search strategy, a vast body of literature was distilled to create a concise collection of 12 articles that describe the methodologies and outcomes related to the thoracic biofidelity of ATDs for non-penetrating blunt ballistic impacts. While this literature review aimed to be comprehensive, it should be noted that not all relevant articles may have been identified. The scope and depth of the research presented herein are based on the availability of sources at the time of the review. The following section presents an annotated list of selected papers and reports identified during this literature review.

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Bir, C. A. (2000). ***The evaluation of blunt ballistic impacts of the thorax*** **[Doctoral thesis, Wayne State University]. Digital Commons®.**

The research by Bir (2000) focused on the development and validation of the 3 Rib Chest Structure (3-RCS) (Figure 2), a specialized biomechanical surrogate designed to simulate and assess high-speed blunt impactor impacts on the human chest. This surrogate was created because the researcher believed the existing surrogates, like the HIII, were inadequate for accurately responding to the high-velocity impacts produced by non-penetrating blunt ballistic impactors. This limitation prompted the 3-RCS to be developed as a more suitable surrogate for such applications.

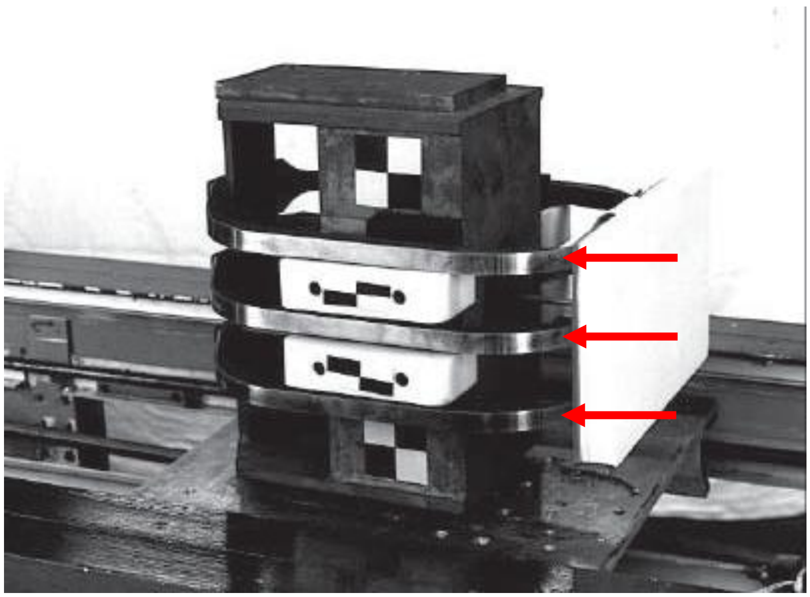

Figure 2. The 3-Rib Chest Structure (3-RCS) is a specialized biomechanical surrogate designed to simulate and assess high-speed blunt impactor impacts on the human chest. The three ribs from a Biofidelic Side Impact Dummy (BIOSID) were used as the foundation for the 3-RCS surrogate are indicated by the red arrows. Figure reproduced with permission from Bir (2000).

The design of the 3-RCS incorporated three ribs from the BIOSID mounted on an 18.1-kilogram (kg) spine box supplemented with internal damping materials to enhance energy dissipation upon impact. After extensive material testing to ensure optimal response characteristics, a urethane bib covered with vinyl-nitrile padding was used to connect the ribs. An important component of the surrogate was the conductive plastic position transducer behind the middle rib. The addition of this transducer allowed for accurate measurement of chest displacement during impacts as it captured data essential for calculating velocity of chest deformation, which are critical for evaluating injury risk.

To test the 3-RCS, the researchers at Wayne State University created three impact conditions. Conditions A and B used a 140-g impactor traveling at 20 and 40 m/s, respectively, to impact the surrogate. Condition C used an impactor with a mass of 30 g traveling at 60 m/s (Table 1). The impactors used in the study were non-compressible polyvinyl chloride (PVC) batons with a 37 mm diameter for all conditions (Figure 3). Notably, these tests were conducted without the presence of body armor. These conditions were also used in a matched-pair analysis with PMHS to create biofidelity corridors; however, a more extensive discussion of the PMHS response corridors was provided in a subsequent paper (Bir et al., 2004). Data analysis focused on analyzing force-time profiles calculated from the accelerometer and calculating viscous criterion (VC) values (e.g., maximum VC [VCmax]) for each test condition (Figure 4 and Figure 5). The VC served as a standardized metric to assess injury potential based on chest deformation dynamics and provided quantifiable data to the researchers for comparison against established injury thresholds.

Table 1. Three Impact Conditions Chosen to Establish Force-Deflection Corridors

Impact Conditions	**Mass (g)**	**Velocity (m/s)**	**Diameter (mm)**
A	140	20	37
B	140	40	37
C	30	60	37

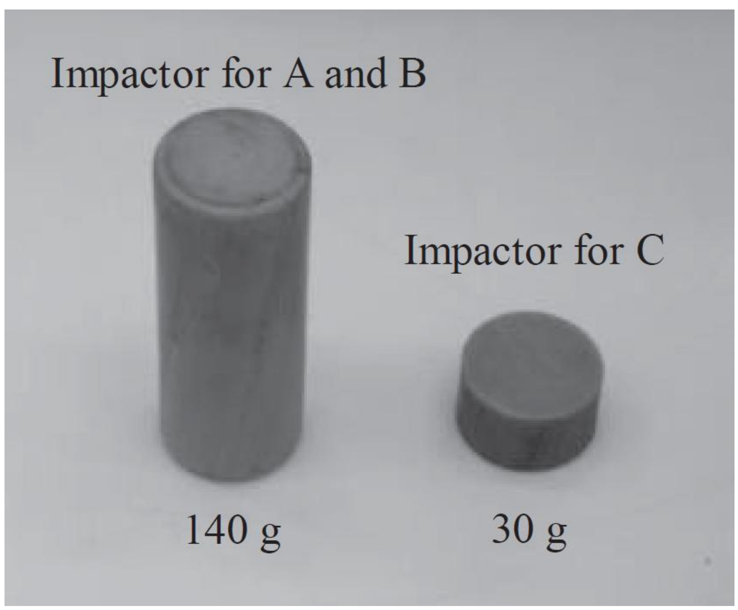

Figure 3. Two impactors were used to determine response to non-penetrating blunt ballistic impacts. The masses of the impactors were 30 and 140 grams (g). Figure reproduced with permission from Bir (2000).

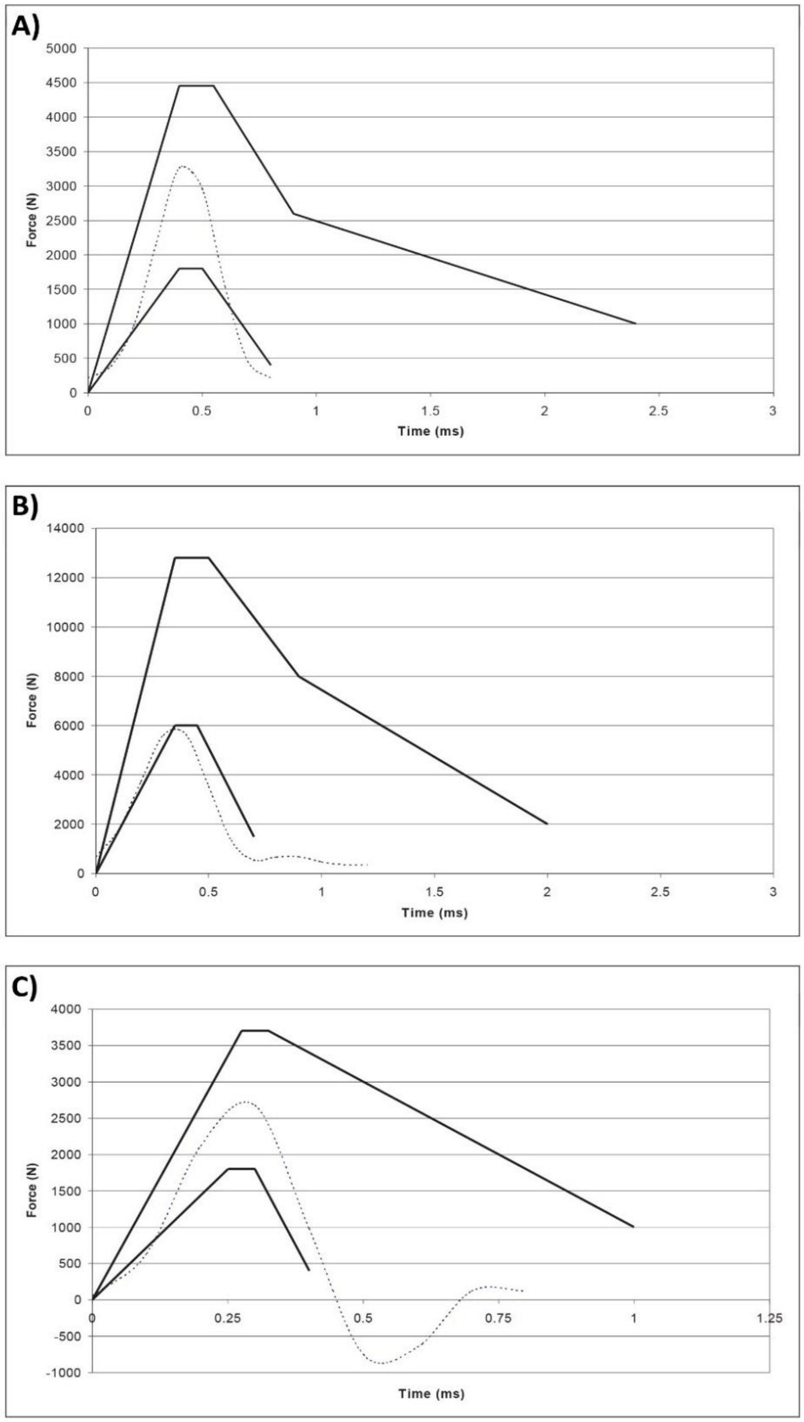

Figure 4. Force-time response of the 3-RCS (dotted line) to impact conditions (A, B, and C) in relation to established PMHS corridors (solid black lines) where the force is in Newtons (N) and time was recorded in milliseconds (ms). Figure reproduced with permission from Bir (2000).

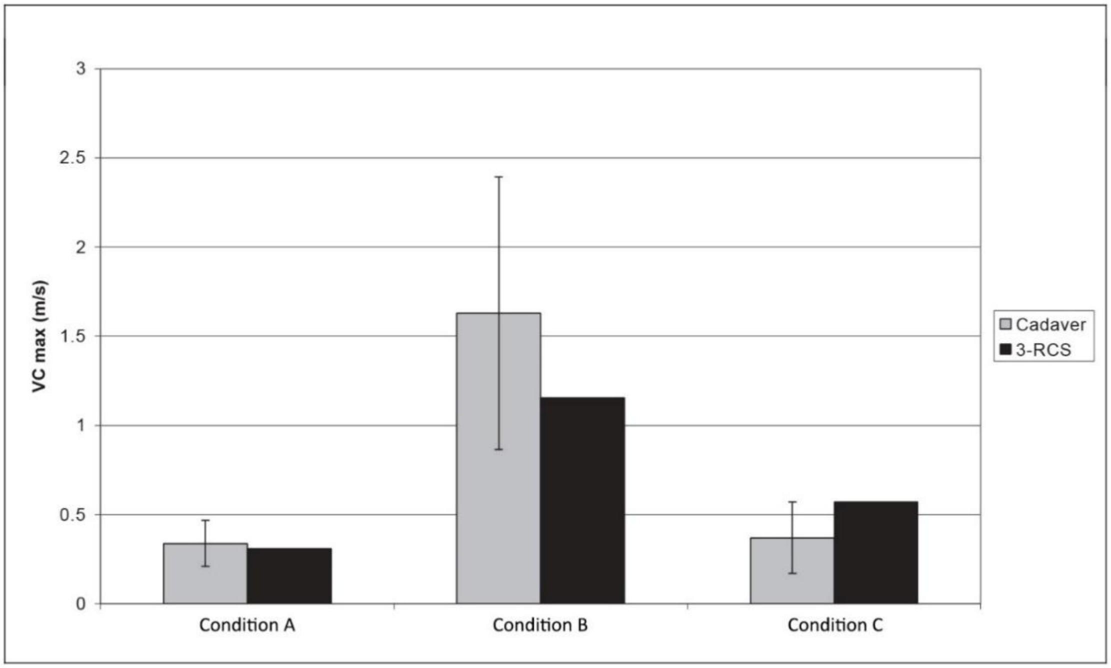

Figure 5. The VCmax for the 3-RCS and PMHS were compared for each of the three impact conditions (A, B, and C). Figure reproduced with permission from Bir (2000).

Initial testing revealed discrepancies between the surrogate response and PMHS data, highlighting the need to optimize the structural components. Iterative adjustments were made to the padding materials and mass of the surrogate to improve its biofidelity across different impact scenarios. The energy saturation of the original padding materials under high-impact forces caused the impactor to contact the urethane bib that held the ribs together. This saturation distorted measurements and decreased the fidelity of mechanical data collected, highlighting the need for improved energy absorption materials in future device iterations. Another limitation was that the transducer used was limited to tracking chest displacement with calculated velocities up to 10 m/s, which restricted the displacement measurements during high-velocity impacts.

Data accuracy of the transducer used during the tests was limited to the impacts performed directly on the middle rib, which constrained the usable impact measurements and did not fully capture the biomechanical responses. One major suggestion by the researchers was to upgrade the transducer technology. Upgrading to a transducer with higher chest displacement velocity tracking capabilities would significantly expand the impact velocity range that could be effectively tested and enhance the applicability of the device across a broader spectrum of ballistic scenarios. Additionally, the researchers suggested integrating displacement transducers into each rib of the 3-RCS. This enhancement would improve the accuracy and reliability of data collection by capturing chest displacement more precisely from various shot placements. As a result of these refinements, subsequent testing phases demonstrated an improved correlation between surrogate response and PMHS data (Figure 4 and Figure 5). Chest displacement measurements and potential injury predictions based on VCmax values showed promising alignment with the PMHS injury thresholds (Figure 5).

Bir, C., Viano, D., & King, A. (2004). Development of biomechanical response corridors of the thorax to blunt ballistic impacts. *Journal of Biomechanics*, *37*(1), 73–79.

The research by Bir et al. (2004) focused on understanding the biomechanical responses of the human thorax to non-penetrating blunt ballistic impacts. This study addressed a significant gap in existing biomechanical data, which primarily consisted of the low-speed, high-mass impacts typical of automotive crashes rather than the high-speed, low-mass impacts relevant to sports injuries and non-lethal munitions. The specific aim was to develop biomechanical response corridors to assess the biofidelity of test surrogates and study the effectiveness of protective gear for non-penetrating blunt ballistic impacts. As part of the author's dissertation research, PMHS response corridors were developed in conjunction with the 3-RCS response corridors (Bir, 2000). A more extensive discussion of these PMHS response corridors is presented in this review of Bir et al. (2004).

Thirteen PMHS were subjected to three distinct blunt impact conditions (A, B, and C) identical to Bir (2000) using a ballistic air cannon. The impactors used in the study, non-compressible PVC batons, were selected to simulate the characteristics of non-lethal munitions and bear similarity to blunt impacts that can occur in some sporting events. Impactors weighing 30 and 140 g each, with a diameter of 37 mm and speeds of 20, 40, and 60 m/s, were used to produce the impacts. The impact conditions are listed in Table 1. These conditions were chosen to generate biomechanical corridors within the lower velocity range of non-penetrating blunt ballistic impacts. The researchers carefully positioned the PMHS so that the impacts would occur at the center of the sternum, directly anterior to the eighth thoracic vertebrae. This specific location was chosen because it is representative of the central chest area, which is commonly affected in real-world scenarios involving non-penetrating blunt ballistic impacts. The sternum's central position in the thoracic cage made it a prime site for transmitting forces to the underlying organs. Understanding the biomechanical response at this location was essential for injury assessment and developing protective gear. The instrumentation used in the study included accelerometers, mounted to the impactors, which allowed impactor response to be recorded during impact. The acceleration data collected and impactor mass were used to calculate the impact force. Additionally, high-speed video cameras were used to record the event. Data normalization was performed to account for variations in PMHS size and to align results with a 50^{th} percentile male standard based on chest depth.

The results revealed distinct biomechanical responses for each impact condition (Figure 6). For condition A, the average peak force was 3,383 ± 761 Newtons (N), with a peak deflection of 22.6 ± 2.8 mm. Condition B resulted in a significantly higher average peak force of 10,620 ± 2,226 N and a peak deflection of 52.3 ± 16.2 mm. Condition C, despite its higher velocity, produced a peak force of 3,158 ± 309 N and a peak deflection of 17.8 ± 4.7 mm. The blunt impact force-time data showed that the impact durations were much shorter than automotive impacts: 0.5 to 1 millisecond (ms) for non-penetrating blunt ballistic impacts versus 40 to 60 ms for automotive impacts.

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Figure 6. Human thoracic biomechanical response corridors for non-penetrating blunt ballistic impacts for impact conditions A (yellow line), B (blue line), and C (purple line) are indicated by the dark solid lines. Force versus deflection curves for each test of the three impact conditions are plotted over the response corridors where force is in Newtons (N) and deflection is in meters (m).

The force-deflection curves established in this study (Figure 6) provided a biomechanical assessment of the PMHS thoracic response to non-penetrating blunt ballistic impacts. The thoracic response under non-penetrating blunt ballistic impact conditions was characterized by higher peak forces and a shorter impact duration than automotive impacts. The amount of compression of the ribcage was also lower for non-penetrating blunt ballistic impacts than automotive impacts (Kroell et al., 1974). The maximum peak force for non-penetrating blunt ballistic impacts reached 12,000 N, whereas automotive impacts typically peak at 6,500 N. However, the non-penetrating blunt ballistic impacts resulted in less chest compression. The highest peak chest compression observed during a non-penetrating blunt ballistic impact was 22.8% for condition B, compared to 41.8% for automotive impacts.

This study highlighted the differences between automotive and non-penetrating blunt ballistic impact responses. The authors noted duration of impact and chest compression of the rib cage as two key differences in the occurrence or non-occurrence of injury between motor vehicle accidents and blunt ballistic impacts. Researchers emphasized the need for further research to refine these corridors and to explore the effects of varying impactor shapes and diameters. Using impactors with different sizes, shapes, and masses could potentially alter the corridor. While the study did acknowledge variability in the physical characteristics of the PMHS as a limitation, it was found that age had no influence on the compliance of the body.

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Bir, C., & Eck, J. (2005). Preliminary analysis of blunt ballistic impacts to the abdomen. In M. D. Gilchrist (Ed.), IUTAM Symposium on Impact Biomechanics: From Fundamental Insights to Applications. *Solid Mechanics and Its Applications*, *124*, 25–32. Springer, Dordrecht.

Bir and Eck (2005) investigated the biomechanical responses of the human abdomen to non-penetrating blunt ballistic impacts, addressing a gap in existing research, which had primarily focused on sternum impacts. The study at Wayne State University aimed to establish biomechanical response corridors for the abdomen, acknowledging that the response to impact varies significantly between different body regions and impact conditions. Bir and Eck reported on a series of experiments in which six PMHS were subjected to impacts from a non-compressible PVC baton (45 g, 37 mm diameter) launched at 60 m/s. The baton was chosen to simulate the characteristics of non-lethal munitions and blunt impacts that can occur in sporting events. The PMHS were carefully positioned to ensure impacts occurred at the epigastric region of the abdomen, and the instrumentation included an accelerometer on the impactor to record its response during impact. The impact force was calculated from the acceleration data and impactor mass, while high-speed video cameras captured the event and provided additional insights into the impact dynamics. To ensure consistency, the data were normalized to account for variations in PMHS size and aligned with a 50th percentile male standard based on chest depth.

The impact event resulted in an average peak force of 4,741 ± 553 N, which was reached within a duration of 0.25 ms. Additionally, the average peak deflection of 22 mm occurred during the initial millisecond of the impact, highlighting the rapid and intense nature of the event. The force-deflection curves can be seen in Figure 7. The authors did not make any conclusions regarding the biomechanical response data and did not discuss any limitations.

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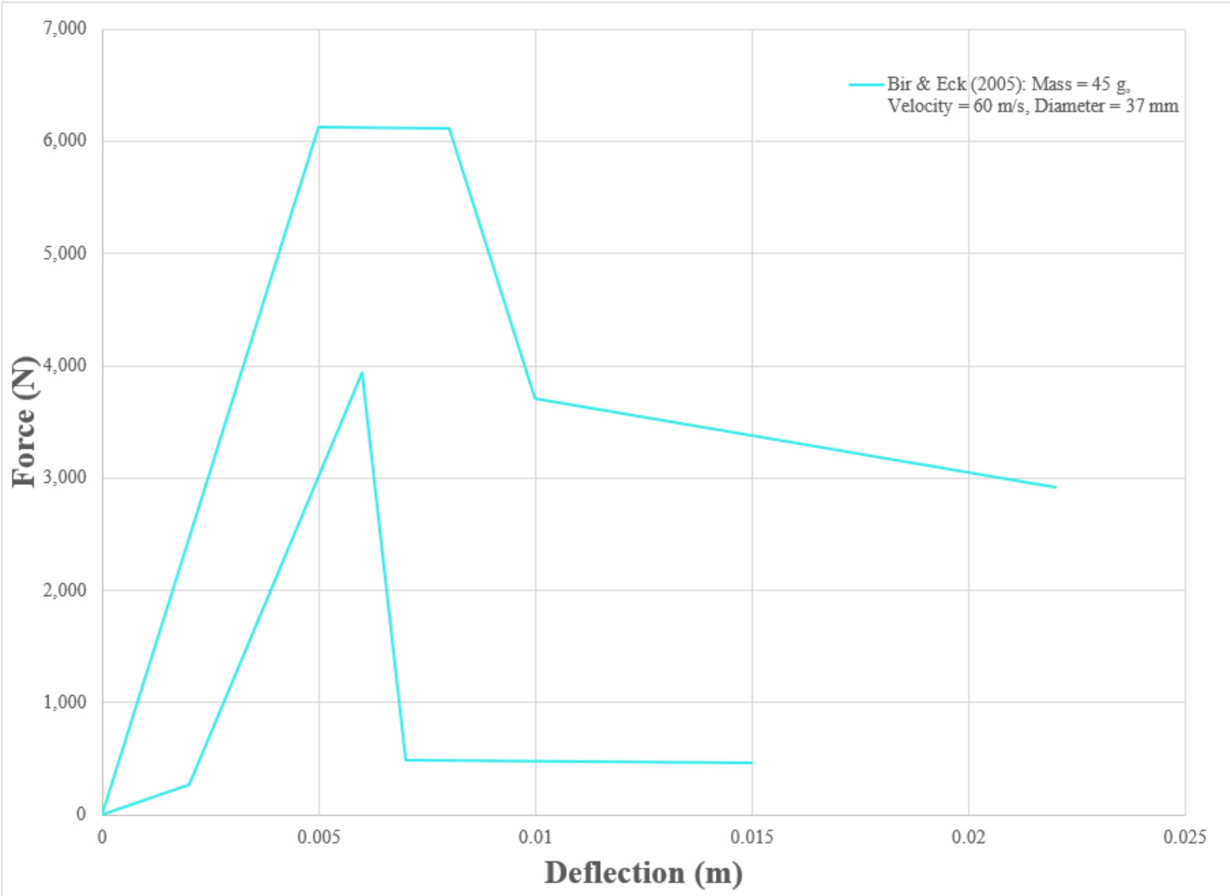

Figure 7. Force-deflection corridors for the epigastric region were developed. The blue lines represent the upper and lower bounds of the response corridors.

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Bass, C. R., Salzar, R. S., Lucas, S. R., Davis, M., Donnellan, L., Folk, B., Sanderson, E., & Waclawik, S. (2006). Injury risk in behind armor blunt thoracic trauma. *International Journal of Occupational Safety and Ergonomics*, *12*(4), 429–442.

Research by Bass et al. (2006) at the University of Virginia aimed to provide a comprehensive evaluation of BABT injuries, focusing specifically on thoracic injuries caused by BFD of hard body armor when subjected to non-penetrating ballistic impacts. Nine PMHS and two human surrogate models were used in the study. The PMHS were carefully selected to match the characteristics of an average adult male in the U.S. population, particularly in terms of body mass and bone density, to ensure the results would be applicable to a broad range of individuals who might wear body armor. The AUSMAN (Figure 8), a reusable mechanical surrogate developed by the Australian Department of Defense – Defense Science and Technology Organization (DSTO) (Rice & Lightsey, 2000), and a clay-based surrogate as specified by the National Institutes of Justice (NIJ) Standard NIJ 0101.04 (NIJ, 2000) were used as the human surrogate models. The NIJ standard established the maximum allowable limit for non-penetrating ballistic BFDs in ballistic protective gear (Bass et al., 2006). The AUSMAN featured a metallic skeletal system coupled with a simulated cardiopulmonary system and was extensively instrumented with a range of sensors, including sternal accelerometers mounted to the upper and lower sternum, thin film stress/strain sensors attached to the sternum, fiber optic pressure sensors to measure local pressure fields behind the impact site, and ultrasonic sensors to measure deformations in the thoracic cavity. This design included flexible components intended to match the natural human tissue responses to impact forces. The AUSMAN was designed to serve as a research tool for studying thoracic deformation from non-penetrating ballistic impacts. The ability of the surrogate to replicate human responses to non-penetrating ballistic impacts was assessed along with its effectiveness as a tool for predicting injury risks.

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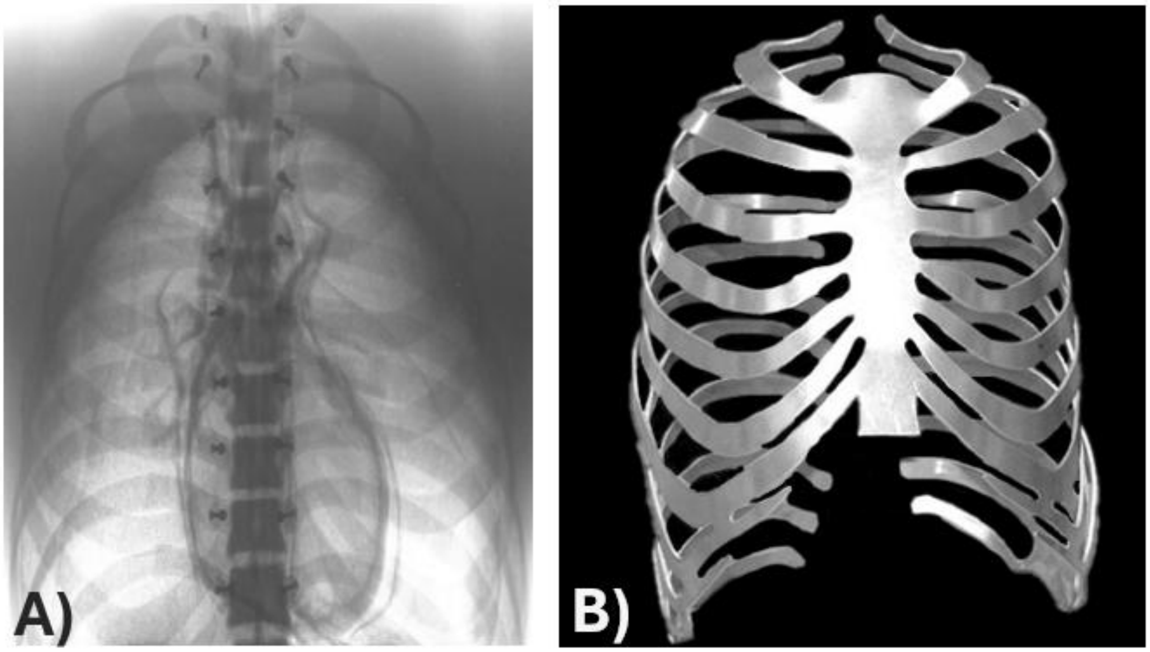

Figure 8. A radiograph of the AUSMAN surrogate shows the simulated cardiopulmonary system. (A) The AUSMAN surrogate had a metallic rib structure (B) Figure A reproduced with permission from Cameron R. Bass, Ph.D.

The body armor tested were made of ultra-high molecular weight polyethylene (UHMWPE). This armor was chosen for its ability to deform under impact without allowing the impactor to penetrate. The researchers targeted the sternum using a 7.62-mm North Atlantic Treaty Organization (NATO) ball round weighing 9.72 g as the impactor and selected a range of velocities between 670 and 800 m/s for the study. The range of velocities were selected based on established thresholds for bone strength and to provide a spectrum of impact energies that could be used to assess the likelihood of thoracic injuries (e.g., rib fractures, sternal fractures, and damage to internal organs).

The PMHS tests resulted in a range of thoracic injuries from minor skin abrasions to severe sternum fractures. Injury severities were closely linked to the impactor velocities and bone density of the individual specimens. Peak forces recorded at the sternum averaged 24,900 ± 1,400 N, which correlated with a 50% risk of sternal fracture, while wearing the body armor. When comparing data from the two surrogate models (AUSMAN and clay) to the PMHS, the AUSMAN demonstrated a reasonable correlation between the impact energy and the resulting deformation of the thorax. However, it was noted that the AUSMAN was stiffer than the PMHS, particularly at the high strain rates associated with non-penetrating ballistic impacts. This stiffness could lead to an underestimation of injury severity in real-world scenarios. While the AUSMAN surrogate provided useful data, the researchers suggested that modifications would be necessary to reduce stiffness and improve biofidelity. Enhancing the ability of the surrogate to replicate the viscoelastic properties of human tissue could lead to more accurate predictions of injury risks. The test series conducted with the NIJ clay-based surrogate showed low correlation of deformation with the range of velocities.

Roberts, J. C., Merkle, A. C., Biermann, P. J., Ward, E. E., Carkhuff, B. G., Cain, R. P., & O'Connor, J. V. (2007). Computational and experimental models of the human torso for non-penetrating ballistic impact. ***Journal of Biomechanics*****,** ***40*****(1), 125–136.**

The research by Roberts et al. (2007) at Johns Hopkins University Applied Physics Laboratory was aimed at developing a 5^{th} percentile male physical human surrogate torso model (HSTM) and a human torso finite element model (HTFEM) to evaluate human torso biomechanical responses during non-penetrating ballistic impacts. The HSTM (Figure 9) was constructed with attention to anatomical accuracy; skeletal structures (i.e., ribs, sternum, cartilage, and vertebral column) and internal organs (i.e., heart, liver, lungs, and stomach) were included in the models. The bones within the HSTM were fabricated using materials designed to mimic the tensile properties of human cancellous bone. The organs were made from silicone gel, which was chosen based on the gel's high-strain rate properties derived from split-Hopkinson bar tests on human tissue. The HSTM incorporated advanced sensing technologies: 1) piezoresistive pressure sensors embedded within the heart, liver, and stomach to monitor internal pressures during non-penetrating ballistic impacts, and 2) accelerometers affixed to the sternum and vertebral column to capture acceleration data.

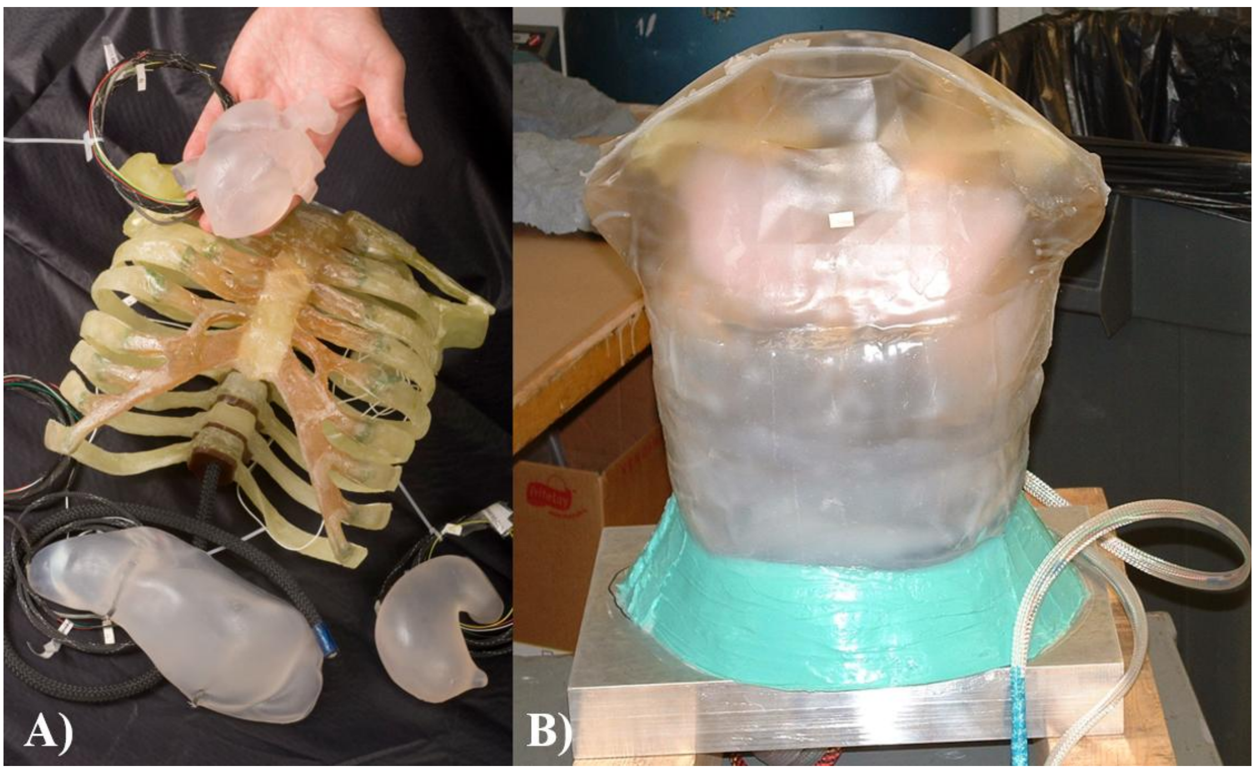

Figure 9. The skeleton and organs of the HSTM included the ribs, sternum, cartilage, vertebral column, heart, liver, and stomach (A). The HSTM was covered with simulated muscle and skin (B) after the pressure sensors and accelerometers were affixed. Figure reproduced with permission from Andrew C. Merkle, Ph.D.

The HTFEM and the HSTM were tested under the same conditions. The HTFEM (modeled) and HSTM were evaluated with 22 caliber ammunition weighing 2.6 g with a 5.69 mm diameter and 9 mm ammunition weighing 8 g. The 22 caliber bullets were fired at a velocity of 329 m/s against a Level I soft armor vest. The 9 mm bullets were tested at different velocities (332 m/s, 358 m/s, and 430 m/s) corresponding to impacts against Level IIA, II, and IIIA soft armor vests, respectively. The HTFEM and HSTM response was evaluated at two locations, the middle of the sternum and the area between the right lobe and the center of the liver. Twenty-six tests were performed on the HSTMs with slight variations in impact locations to avoid repetitive damage to specific areas on the surrogate to ensure the reliability of the data collected.

It was noted that organs located further from the impact point experienced significantly lower pressures. Acceleration data, specifically from the sternum, showed that the HSTM and HTFEM had excellent agreement in their acceleration profiles. Peak accelerations differed by less than 10% between the impact points. Notably, the highest sternum acceleration recorded was approximately 23,000 G, where G is acceleration due to gravity, during a Level II impact, where a 9 mm bullet struck at 358 m/s. Researchers identified discrepancies in the pressure readings for organs located farthest from the impact, which were attributed to the directional sensitivity of the sensors and the influence of lateral loading on the sensor housing. The researchers suggested that future work should include further validation against experimental data from PMHS tests, which was not conducted during this study.

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Bolduc, M., & Anctil, B. (2010, 13-17 September). Improved test methods for better protection, a BABT protocol proposal for STANAG 2920. *Proceedings of the Personal Armour Systems Symposium (PASS)*, Quebec City, QC.

At Defence Research and Development Canada (DRDC) Valcartier, research was performed by Bolduc and Anctil (2010) to develop and evaluate the Blunt Trauma Torso Rig (BTTR) (Figure 10) to assess BABT produced by non-penetrating ballistic impacts. The BTTR was proposed as a more biofidelic tool to replace the traditional RP1 clay method used in the NATO Standard for Ballistic Test Method for Personal Armor Materials (Standardization Agreement [STANAG] 2920, Edition 3) (NATO, 2007). While the results of non-penetrating ballistics research using RP1 clay have provided many safety recommendations, the ability of RP1 to assess what is happening to tissue during ballistic impact is limited. To address this gap, the BTTR was developed to offer a more realistic assessment of the risks associated with non-penetrating ballistic impacts on body armor.

Figure 10. The first generation BTTR had a cylindrical shape based on average chest breadth and approximated curvature for correct armor fit. Figure reproduced with permission from Biokinetics and Associates, Ltd.

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The BTTR consisted of a cylindrical membrane that allowed a 360-degree usable area for impact testing; consequently, multiple impacts to the BTTR are possible without frequent membrane replacement. The membrane was equipped with displacement sensors to measure the deflection caused by non-penetrating ballistic impacts. Armor samples were marked with predefined shot locations, mounted on the BTTR, and adjusted to ensure the shot location was aligned perpendicularly to the line of fire. Non-perforation velocity test shots were fired, and membrane displacement was recorded. The inherent force-deflection characteristic of the membrane was not reported. Membrane deflection was measured in terms of rate and acceleration, and measurements were processed using a moving-average function to calculate the VC. The study also used a parametric model originally used to estimate the probability of blunt trauma lethality from animal test data (U.S. Congress, 1992).

Testing was conducted using 12 different impactors with masses ranging from 8 to 378 g and diameters ranging from 18 to 97 mm. The BTTR was directly impacted at velocities ranging from 10 to 154 m/s. A series of parameters (peak and average deflection, peak velocity, peak acceleration, and VCmax) were derived from the membrane deflection measurement and plotted against the probability of lethality to identify a suitable injury predictor. Results from the study showed that no single parameter could accurately predict injury severity across all impactor types; however, the VCmax demonstrated a promising correlation with injury severity for impacts with similar diameters regardless of impactor weight. The BTTR's measurements were compared to historical PMHS data from non-penetrating ballistic impact experiments (Bass et al., 2006) on biological models. Test results showed that the BTTR could predict injury levels corresponding to the protection offered by soft and rigid body armor systems. The probability of injury as functions of membrane peak deflection and VCmax were reported.

For soft armor impacts, the BTTR predicted a low risk of severe injuries, which aligned with minor to moderate injuries observed in PMHS data reported by Mackiewicz et al. (2002). For rigid plates, the BTTR predicted a higher risk of severe injuries that were consistent with the PMHS tests. The study highlighted the limitation of traditional methods (such as RP1 clay) to replicate the human body's response during non-penetrating ballistic impacts and emphasized the need for more advanced tools, like the BTTR, to analyze the BABT phenomenon.

At this stage, the BTTR was proposed to complement the existing RP1 clay method, not replace it, due to the limited validation of the new tool. Further validation and refinement of the BTTR were recommended to address technical issues and improve the surrogate's biofidelity. The initial validation highlighted some limitations in the ability of the BTTR to provide a universal injury prediction across all impactor types. The researchers suggested that future research should refine the measurement parameters and improve the accuracy of injury predictions. Incorporating more advanced sensor technologies could enhance the BTTR's predictive capabilities.

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Dau, N. (2012). ***Development of a biomechanical surrogate for the evaluation of commotio cordis protection*** **[Doctoral dissertation, Wayne State University]. Digital Commons®.**

Dau (2012) investigated the thoracic responses of PMHS to impactor impacts with the goal of validating existing surrogate models and informing the development of more accurate and reliable surrogates for simulating human thoracic responses to blunt trauma. PMHS ribs were instrumented with strain gauges to detect fractures, and triaxial accelerometers were attached at the fourth thoracic vertebrae (T4) on the spine to measure thoracic acceleration during impacts. Additionally, the left heart ventricle of each PMHS was pressurized with a saline solution to mimic physiological conditions during the impact, and a pressure of 80 millimeters of mercury (mmHg) was maintained using a specialized catheter system.

Lacrosse balls were mounted onto shafts instrumented with an Endevco 7270 20K accelerometer (Figure 11) and launched using a compound bow. The study examined impacts at four different speeds: 30 miles per hour (mph) (13.4 m/s), 40 mph (17.9 m/s), 50 mph (22.4 m/s), and 60 mph (26.8 m/s). The total impactor mass, including the ball, shaft, and accelerometer mount, was 188.4 g for the two lower impact speeds (13.4 and 17.9 m/s) and 214.5 g for the two higher impact speeds (22.4 and 26.8 m/s). The diameter of the lacrosse ball was 64 mm. The impacts were delivered to the cardiac silhouette of the thorax.

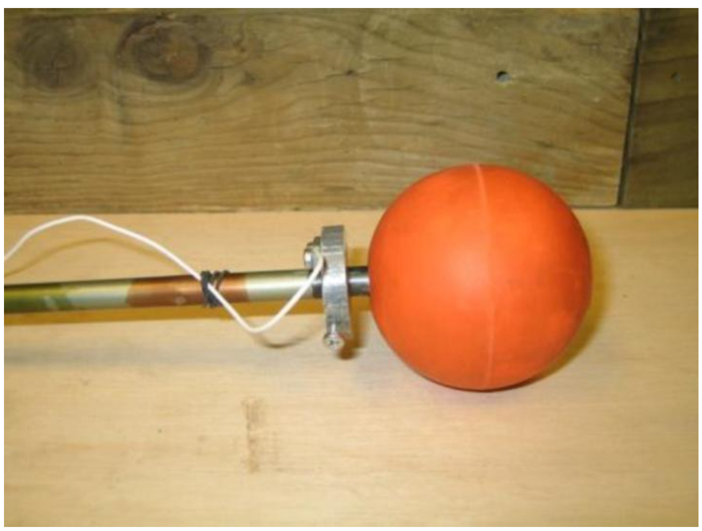

Figure 11. The ball shaft impactor was designed by using a lacrosse ball attached to an aluminum shaft. The accelerometer was attached to the impactor via an aluminum disc that was mounted to the shaft directly behind the ball. Figure reproduced with permission from Dau (2012).

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The acceleration was multiplied by the mass of the impactor to approximate the force versus time during the impact. High speed video tracking was used to determine deflection versus time and then synchronized with the force data. Force versus displacement data were plotted with standard deviations (Figure 12). The peak impact forces recorded were 1,299 N, 1,817 N, 2,044 N, and 2,353 N for the respective impact speeds of 13.4, 17.9, 22.4, and 26.8 m/s. Corresponding chest deflections ranged from 2.1 centimeters (cm) at 13.4 m/s to 3.7 cm at 26.8 m/s with impact durations under 4 ms. The PMHS results were compared to those from porcine tests from this study (Figure 13). At lower speeds (13.4 and 17.9 m/s), the porcine model's peak impact forces were within the response corridors established by the PMHS data, indicating some level of biofidelity. However, at higher speeds (22.4 and 26.8 m/s), the peak forces in porcine models exceeded those observed in the PMHS, suggesting that the thoracic biofidelity of the porcine model may be inadequate for simulating high-speed impacts in humans. The porcine model produced higher peak loads than PMHS by 25% at 22.4 m/s and 33% at 26.8 m/s, which could be attributed to the differences in thoracic anatomy, such as the deeper thorax in swine compared to humans.

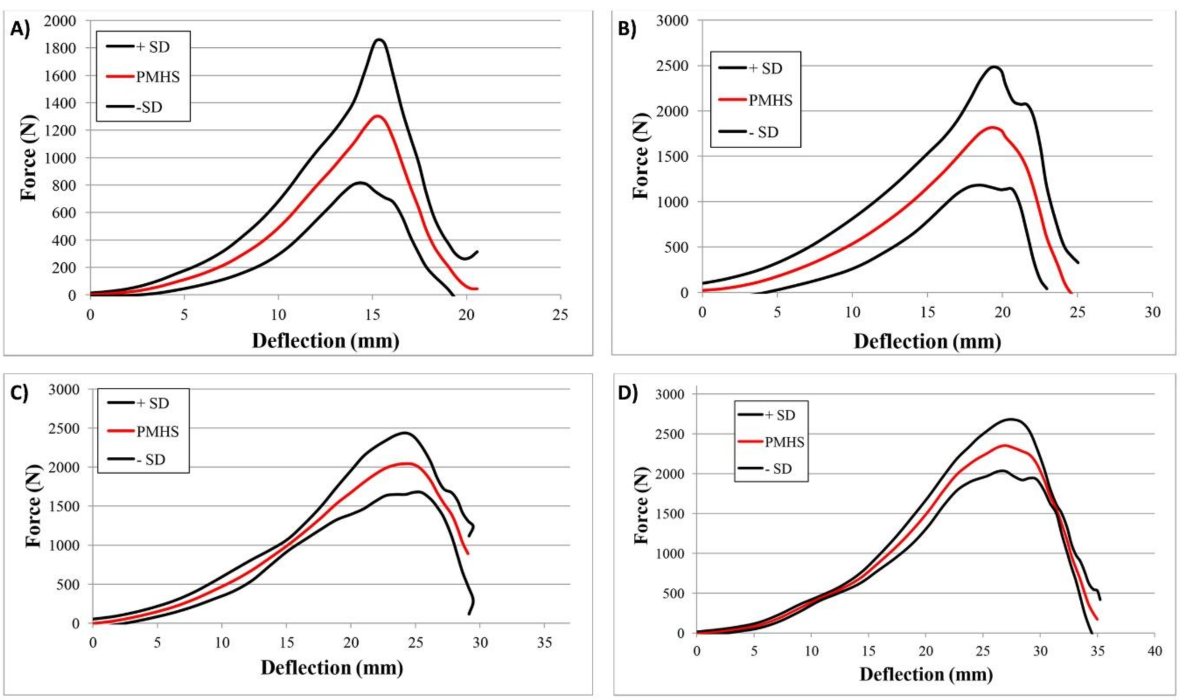

Figure 12. The force-deflection biomechanical response corridors for PMHS at (A) 13.4, (B) 17.9, (C) 22.4, and (D) 26.8 m/s demonstrate the variability in biomechanical responses under different impact conditions. Figure reproduced with permission from Dau (2012).

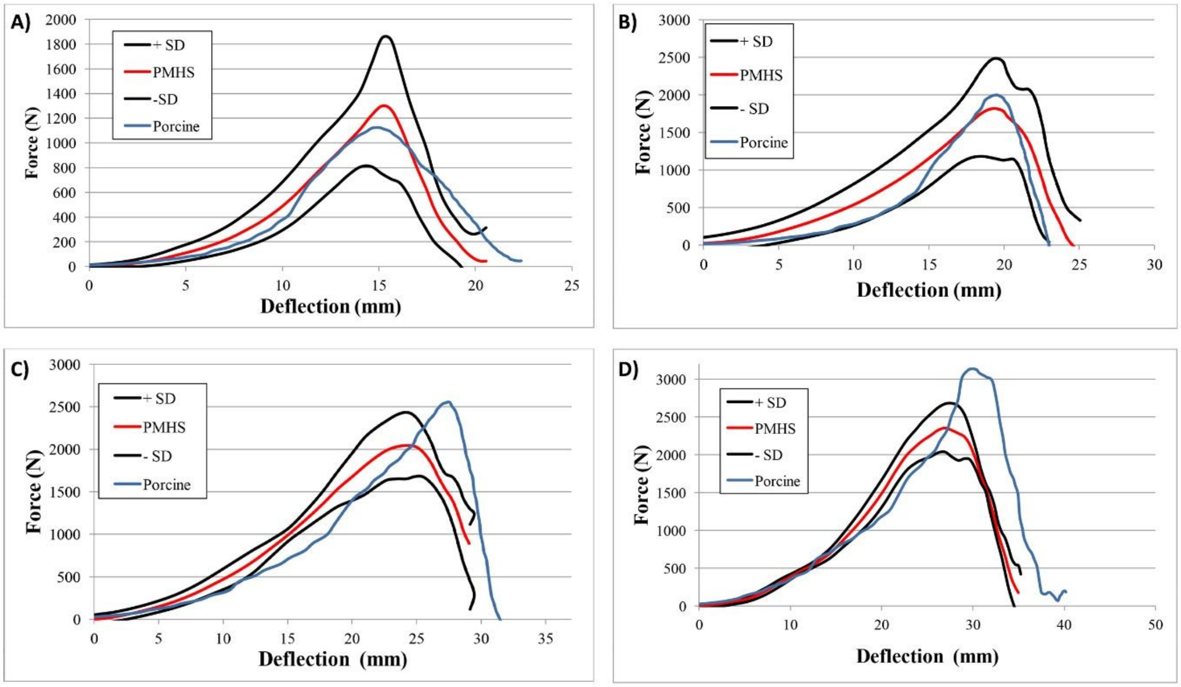

Figure 13. The force-deflection biomechanical response corridors for PMHS and porcine at (A) 13.4, (B) 17.9, (C) 22.4, and (D) 26.8 m/s demonstrate the variability in biomechanical responses under different impact conditions. Figure reproduced with permission from Dau (2012).

In this study, the evaluation of the existing surrogates revealed significant discrepancies between their responses and the human response corridors (Figure 14). The biofidelity of the 3-rib ballistic impact dummy (3-RIB), HIII 5th percentile female (5F), and HIII ten-year-old (10yo) was compared to the PMHS data and scored using an external biofidelity rank. An external biofidelity score greater than 1 indicates that the response of the surrogate differed from the PMHS data by more than one standard deviation. The 3-RIB, HIII-5F, and HIII-10yo all exhibited external biofidelity scores above 1. Specifically, the 3-RIB model had the poorest performance with an external biofidelity score of 3.576, followed by the HIII-5F with a score of 2.767, and the HIII-10yo with a score of 2.107. These findings highlighted the inadequacy of these existing surrogates for accurately replicating human thoracic responses to blunt impacts under these loading conditions. The poor external biofidelity scores could be attributed to the limitations of the surrogates. The 3-RIB model lacks anatomical considerations; the model features a simplified thoracic structure without shoulders or attachment points for protective gear. The HIII-5F and HIII-10yo surrogates, while more anatomically detailed, were designed for automotive impacts, which have different loading conditions than those encountered in sports or military environments.

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Additionally, the study emphasized several gaps and limitations in the methods used to simulate human thoracic response. The advanced age of the PMHS presented a significant limitation because it diverged from the target adolescent population. The absence of lung inflation during testing might have altered the thoracic response, particularly in terms of the soft tissue's contribution to impact resistance. Additionally, the inability of the PMHS to sustain repetitive impacts, especially at higher speeds, restricted the dataset and limited the researcher's ability to fully characterize human response across different impact conditions. The author indicated that future work should focus on addressing these limitations, potentially using specimens with ages appropriate to the population being studied and the incorporation of lung inflation techniques to replicate real-world impact conditions more accurately.

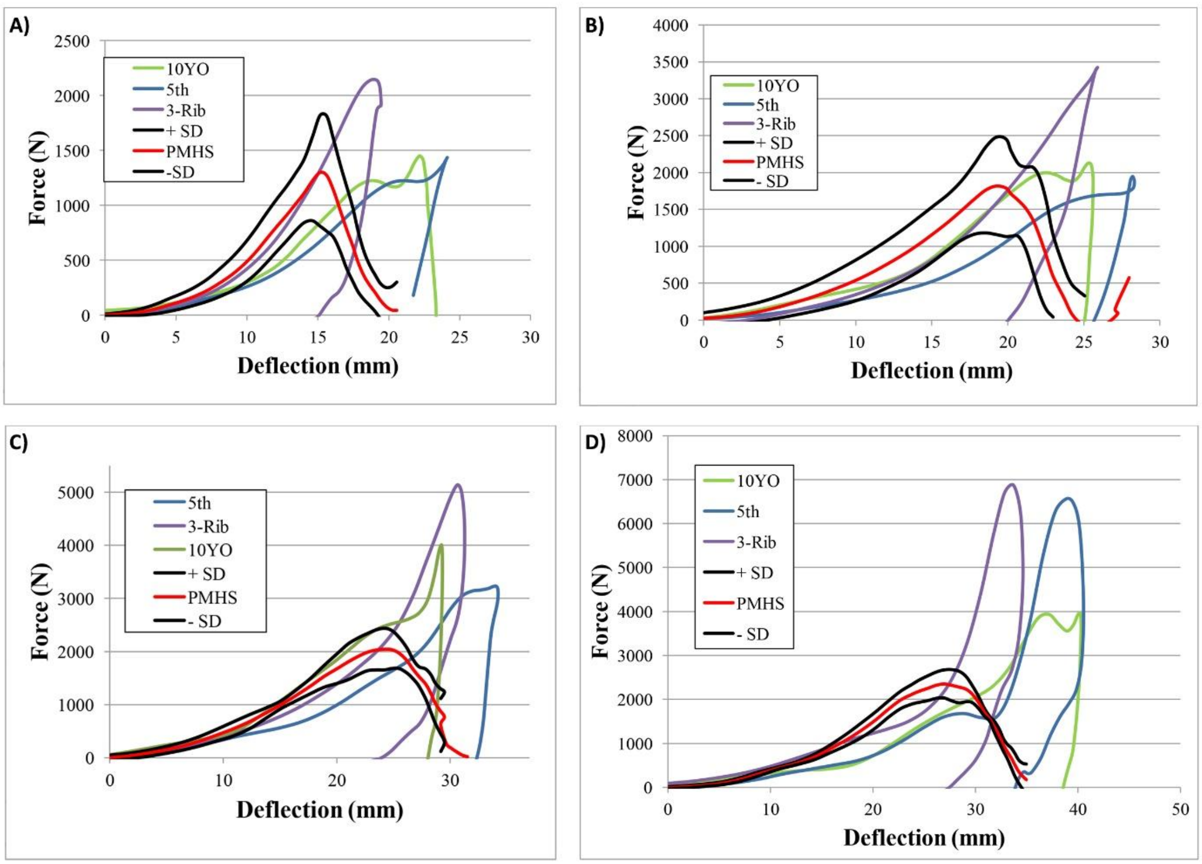

Figure 14. The force-deflection biomechanical response corridors for existing surrogates at (A) 13.4, (B) 17.9, (C) 22.4, and (D) 26.8 m/s demonstrate the variability in biomechanical responses under different impact conditions. Figure reproduced with permission from Dau (2012).

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Sedberry, K., & Foley, S. (2019). Modular human surrogate for non-lethal weapons (NLW) testing. *Journal of the Defense Systems Information Analysis Center, 6*(1), 16–23.

The research at Defense Systems Information Analysis Center, conducted by Sedberry and Foley (2019), described the development of a modular human surrogate (MHS) designed for non-lethal weapon (NLW) testing (Figure 15). The surrogate was designed to be modular, allowing for easy replacement of parts and sensors based on the specific testing requirements. The MHS included an anatomical head with removable eyes and ears, neck attachments that could be configured for either fixed or flexible interfacing, and two different torso designs aimed at testing blunt impacts and electromagnetic (EM) weapons.

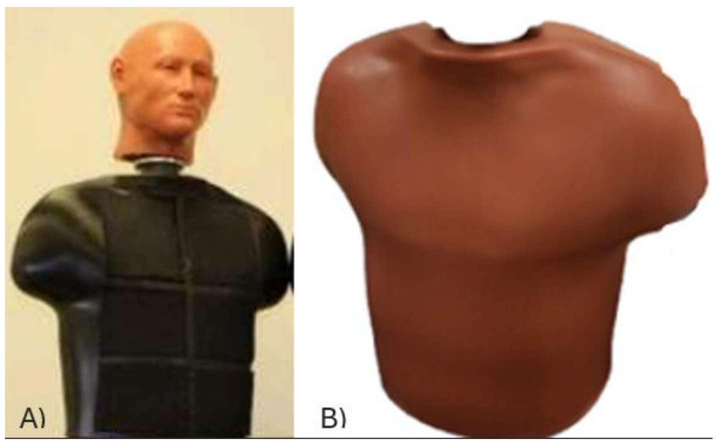

Figure 15. A modular NLW surrogate was designed with sensors (A) and a blunt impact torso (B) embedded with pressure sensors in a soft tissue simulant and an accelerometer on the sternum. Figure reproduced with permission from Sedberry and Foley (2019).

The blunt impact torso is particularly notable for its array of pressure sensors embedded within a soft tissue simulant, covered by a realistic skin-type material. This design allows the sensor suite to be easily changed depending on the expected blunt impact forces. The surrogate was equipped with a six-degree-of-freedom sensor at the top of the neck to measure linear and angular movement, and pressure sensors and an accelerometer were placed on the sternum of the torso to capture the loads exerted during impact.

While researchers aimed for the MHS to mimic human biomechanical responses closely, detailed numerical results for the blunt torso were not presented and specific comparisons to any published thoracic biofidelity response data were not made in the report. Thus, no determination can be made on the capabilities of this surrogate.

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Shewchenko, N., Fournier, E., Bayne, T., Magnan, S., & Bourget, D. (2020, 11 October). The development of the f-BTTR and its use for hard armour testing. *Proceedings of the 2020 Personal Armour Systems Symposium*, Copenhagen, Denmark.

Shewchenko et al. (2020) created the flat Blunt Trauma Thoracic Rig (f-BTTR) at Biokinetics and Associates, Ltd. (Figure 16) to enhance the accuracy and reliability of measuring BFD of hard armor after non-penetrating ballistic impacts. This advancement addressed limitations observed in the cylindrical BTTR design, which relied on single-point deformation measurements and lacked adequate support for rigid armor, which led to inconsistent and unreliable data. The inadequacies in biofidelity and measurement capacity of the BTTR hampered its effectiveness in accurately assessing injury risk. The f-BTTR was designed to allow for three dimensional (3D) transient deformation measurement, thereby assessing additional response metrics that may be indicators of injury risk including the area, volume, and shape of the BFD more accurately.

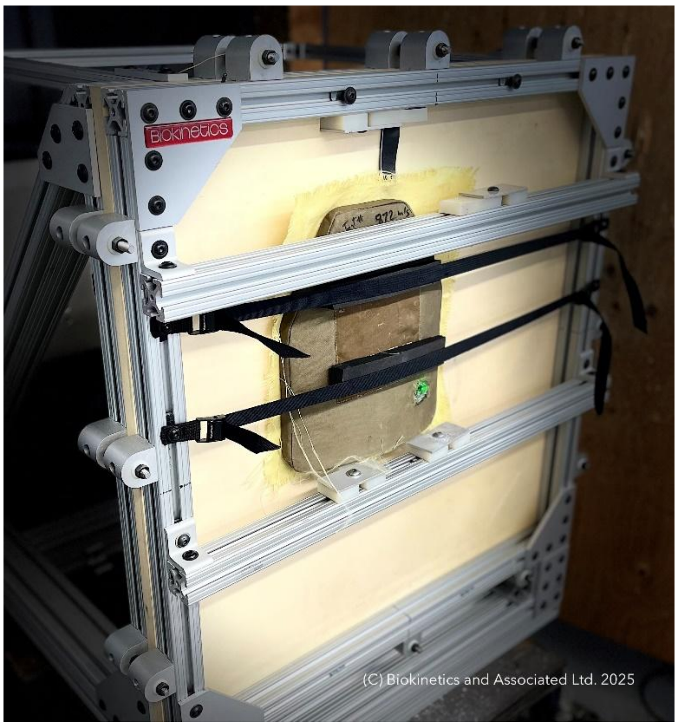

Figure 16. The f-BTTR system membrane setup and 3D BFD measurement system was designed to allow for 3D transient measurements. Figure reproduced with permission from Biokinetics and Associates, Ltd.

The f-BTTR was conceived as a solution to the challenges of the BTTR, incorporating a flat membrane that facilitated 3D transient deformation measurement using laser displacement transducers (LDT) (Bolduc & Anctil, 2010). This flat design allowed for a more detailed and comprehensive measurement of deformation and provided better support for hard armor plates. This design ensured the measurements obtained were reliable and consistent. The f-BTTR used two orthogonal laser profilometers to capture detailed 3D deformation profiles, which were then processed to calculate metrics (e.g., peak deflection, velocity, volume, and deformation). The flat design of the f-BTTR reduced the sensitivity of injury metrics to errors in armor positioning and shot alignment, which can be an issue with curved surfaces like the cylindrical BTTR that require precise placement to within a few millimeters. To further enhance its capabilities, the system could be rotated to change the impact locations or achieve varying degrees of impact obliquity. The biofidelity of the f-BTTR was evaluated through a comparison of its deformation values with those of PMHS. Targeted deformation results are provided in Table 2.

Table 2. Biofidelity Response Targets for the f-BTTR

Body Region	Impactor	Diameter (Ø) (mm)	Mass (g)	Target Velocity (±2 m/s)	Target Deflection Range (mm)
Thorax	Baton	37	140	40	45 to 65
Abdomen	Baton	37	48	60	26 to 34
Thorax	Lacrosse ball	65	215	27	30 to 42

Note. Table modified with permission from Shewchenko et al. (2020).

The f-BTTR generally complied with the peak deflection targets and response corridors for the 48 g mass baton traveling at 60 m/s and the 215 g mass lacrosse ball traveling at 27 m/s (Figure 17B & C). However, the average peak membrane deflections were 11% below the lower bound target for impacts with the 140 g mass baton traveling at 40 m/s. Figure 17 shows that the membrane deformation velocity during the first few milliseconds generally met the requirements for all response targets.

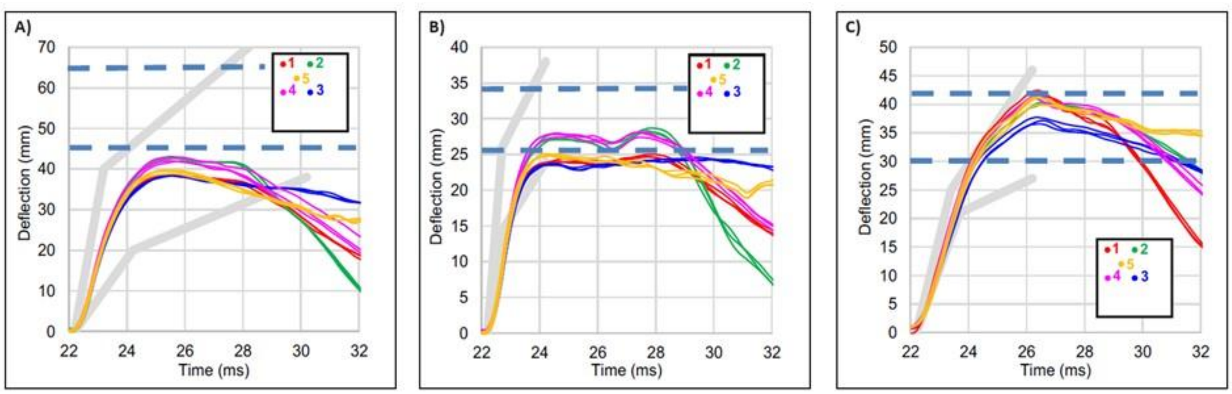

Figure 17. Deflections of the f-BTTR were plotted against biofidelity corridors (gray lines) and target deflections (horizontal blue dashed lines) with each of the five tests shown in distinct colors. The results are shown for three specific test scenarios: (A) a 140 g impactor impacting the thorax at 40 m/s, (B) a 48 g impactor impacting the abdomen at 60 m/s, and (C) a 215 g impactor impacting the thorax at 27 m/s. Figure reproduced with permission from Shewchenko et al. (2020).

The f-BTTR exhibited consistent trends that aligned well with biomechanical responses without large discontinuities. However, the researchers recommended further validation of the f-BTTR against a broader range of biomechanical studies to enhance surrogate relevance and sensitivity for injury assessments. They suggested restricting impacts to the central area of the membrane for better consistency and considering lateral extensions of the membrane to reduce edge constraints. Additionally, they proposed refining the membrane material and thickness to improve compliance with specific biofidelity targets.

The study also used RP1 clay as a backing material to compare the response of the f-BTTR to different armor support conditions. A 7.62 mm NATO ball round impacted armor at a velocity of 847 ± 9.1 m/s, causing an indentation in the clay backing. Indentation depth, volume, and surface area were subsequently measured. The results in Table 3 showed that the clay infill condition resulted in larger peak deformations and volumes compared to the air gap condition. The study also compared the response of the f-BTTR membrane to different armor infill conditions and found that the membrane was more sensitive to variations in armor support than the clay. The higher stiffness of the clay and full support by the containment frame affected the measurement results, highlighting the importance of considering these factors in armor testing.

Table 3. Test Results of Hard and Soft Body Armor Systems on the f-BTTR and Ballistic Clay for Different Support Conditions

Test Device	Armor Support Condition	Test #	Impact Velocity (m/s)	Max Indentation (mm)	Max Velocity (m/s)	Max Volume (cm^3)
f-BTTR	Air gap/edge supported	1	846	18.6	23.0	396
f-BTTR	Fully supported polyurethane infill	2	851	24.1	20.0	610
f-BTTR	Partially supported polyurethane infill	3 4 5	849 841 839	22.8 23.3 23.9	17.6 18.7 20.2	542 598 672
Clay block	Air gap/edge supported	6	841	15.1	NA	40
Clay block	Fully supported clay infill	7	848	31.3	NA	113

Note. Table modified with permission from Shewchenko et al. (2020).

Other limitations noted were low spatial resolution and a low sampling rate of the measurement system, indicating a need for higher resolution profilometers and potentially integrating digital image correlation systems for validation. Measurement constraints, including the width limit of the profilometers and sensitivity to off-target impacts, were also noted as limitations. Although there were limitations, the f-BTTR showed more consistent peak deformation readings and had lower standard deviations than traditional ballistic RP1 clay. Comparative tests revealed larger peak deformations and volumes under specific conditions, suggesting distinct deformation mechanics between the f-BTTR membrane and ballistic clay.

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Yan, W., Yao, X., Wang, Y., Jin, Y., & Wei, W. (2020). Experimental study of the mechanical response of a physical human surrogate thoracic model impacted by a rubber ball. *Journal of Physics: Conference Series*, *1507*(10), 102032.

Yan et al. (2020) focused on developing and evaluating a physical thoracic model surrogate named the "skin-skeleton-organs" (SSO) that was designed to assess the mechanical responses of the human thorax to impacts from rubber bullets. This model was constructed at the Science and Technology on Transient Impact Laboratory and used computed tomography (CT) scans of a Chinese adult male to provide realistic anatomical representation. The surrogate is comprised of three primary components, the skin and muscle, internal organs, and the skeletal system (Figure 18). The skin and muscle were modeled using polyurethane elastomer, which was chosen for its ability to mimic the flexibility and impact absorption characteristics of human tissues. The internal organs (i.e., heart, lungs, liver, and stomach) were created from various viscoelastic materials that replicated the deformation and pressure response of real human tissues. The skeletal structure, which included the sternum, ribs, and spine, was composed of a thermosetting resin mixed with calcium phosphate and fiberglass. This design simulated the strength and rigidity of human bones.

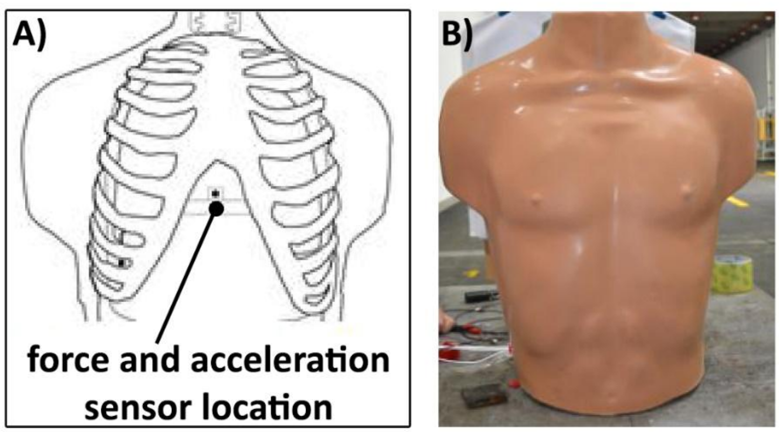

Figure 18. The SSO skeleton with force and acceleration sensor (A) and the complete SSO model with skin (B). Figure reproduced with permission from Yan et al. (2020).

Researchers impacted the SSO with 16 mm diameter rubber balls fired from an air gun, replicating less-lethal scenarios. The authors did not mention the weight of the rubber balls. Three velocity ranges were used: low (85 to 90 m/s), moderate (110 to 115 m/s), and high (130 to 135 m/s). The air gun was positioned 5 meters from the surrogate. Targeted impact locations were carefully chosen to align with the mechanical sensors embedded in the chest of the model. The sensors included piezoelectric pressure sensors placed in the internal organs to measure pressure changes, and a sensor attached to the sternum to record force and acceleration (Figure 18).

To establish an experimental method for evaluating sternum injuries, the researchers collected and analyzed the maximum force and acceleration exerted on the sternum. The results from the non-penetrating ballistic impact tests showed that the internal pressure in the organs, as well as the force and acceleration experienced on the sternum, increased with higher impactor velocities (Figure 19 and Table 4). The forces measured at the sternum ranged from an average of 3,559.0 N at low velocities to an average of 4,394.4 N at high velocities. The acceleration ranged from averages of 2,217.9 to 3,495.3 G across the same velocities. The pressure sensors embedded in the organs recorded peak pressures that corresponded to the proximity of the impact site. The organ closest to the impact experienced the highest pressure. These results were consistent across multiple tests and demonstrated the ability of the surrogate to replicate mechanical responses reliably.

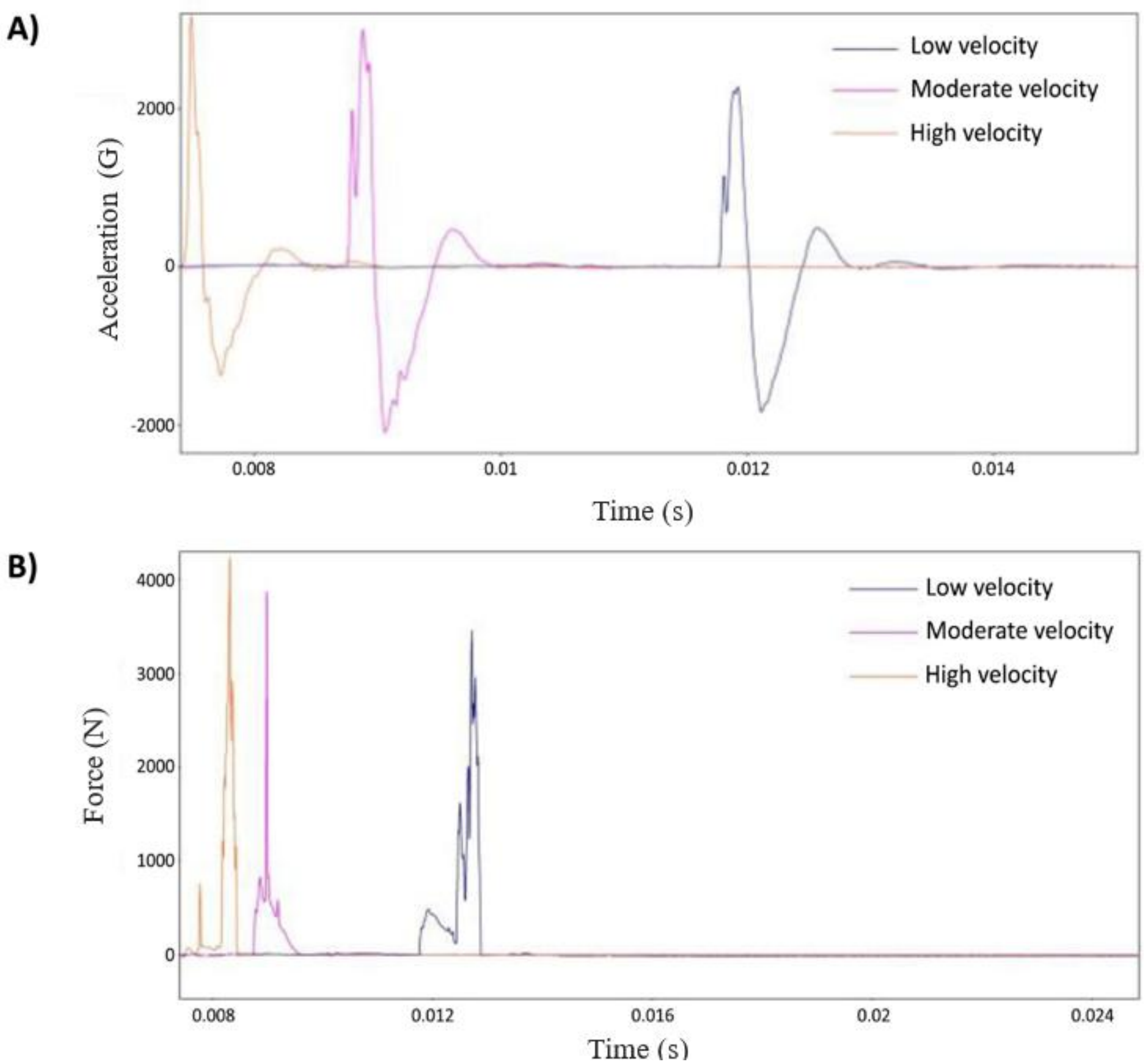

Figure 19. The typical time histories of the acceleration (A) and force (B) on the sternum for different velocities. Figure modified with permission from Yan et al. (2020).

Table 4. Force and Acceleration on the Sternum

Approximate Impact Velocity (m/s)	**Force (N)**	**Acceleration (G)**
85	3,653.0	2,237.8
85	3,456.7	2,271.1
85	3,567.4	2,144.8
115	4,508.6	2,607.9
115	4,261.2	2,717.2
115	3,872.8	2,996.7
135	4,235.8	3,170.0
135	4,578.3	3,746.9
135	4,369.2	3,568.9

Note. Table reproduced with permission from Yan et al. (2020).

The SSO surrogate was effective in replicating the structural anatomy and mechanical properties of the human thorax. One major study limitation was that the materials used in the model may not have fully captured the complex behavior of human tissue under non-penetrating ballistic impact, which is crucial for a more comprehensive understanding of injury mechanisms. Additionally, there were no comparisons made between the mechanical response parameters of the surrogate and those of live animals or PMHS. Furthermore, the restriction of impact locations to the sternum is a significant limitation, as it does not account for the potential variability in impact locations that can occur in body armor testing of BABT applications. Yan et al. (2020) suggested that future work should focus on refining the SSO materials to better mimic the mechanical and physiological properties of human tissues. Comparative studies should also be conducted to validate surrogate performance against real biological responses.

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Jenerowicz, M., Bauer, S., Thoma, O., Boljen, M., Riedel, W., & Straßburger, E. (2023, October 16). Evaluation of behind armor blunt trauma (BABT) - Numerical investigation with GHBMC M50 and dummy tests with CTS-Primus breakable thorax. *Proceedings of the 33rd International Symposium on Ballistics*, Bruges, Belgium.

The research by Jenerowicz et al. (2023) aimed to evaluate and compare the results from testing the PRIMUS breakable biofidelic crash dummy (CTS® Crash-Test Service, Münster, Germany) (Figure 20) and the General Human Body Model Consortium (GHBMC) numerical simulations against data from PMHS tests to evaluate the BABT capabilities of the PRIMUS.

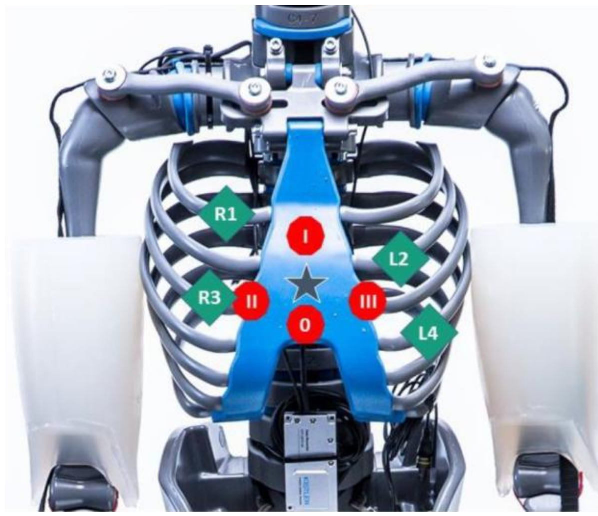

Figure 20. The position of instrumentation on the PRIMUS thorax (strain gauges right: R, left: L, rib levels 1 through 4: R1, L2, R3, and L4), two accelerometers in the mid-sternum, rib levels 2 through 3 and corresponding side on the dorsal vertebra 9th thoracic vertebrae (T9), red marked target zones 0 through III (0: mid-sternum under the accelerometer, rib levels 3 through 4; I: mid-sternum above accelerometer, rib levels 1 through 2; II: end of R3 at the junction with the sternum; III: end of L3 at the junction with the sternum). Figure reproduced with permission from Jenerowicz et al. (2023).

The experimental setup at Fraunhofer-Institute for High-Speed-Dynamics featured a PRIMUS breakable dummy that represented an average male with a height of 175 cm and weight of 77.8 kg (69th percentile male [Gordon et al. (2014)]). This surrogate was equipped with strain gauges and accelerometers to measure the forces and accelerations experienced during impact with a hard-ballistic plate consisting of silicon carbide and ultra-high molecular weight polyethylene. To ensure safety and repeatability in the tests, polycarbonate impactors were created to mimic the mass and impact characteristics of a 7.62 mm bullet. These impactors weighed 9 g, had a diameter of 19.9 mm, had a length of 28.0 mm, and were fired using an air cannon. The authors did not specify the shape of the impactor, such as whether they were pointed or flat.

The Blunt criterion (BC) is a measure developed by the Department of Defense to predict injuries from blunt impactors. It considers factors such as the mass, velocity, and diameter of the impactor, as well as the mass and thickness of the body wall of the target (Kapeles & Bir, 2019). The BC was used to assess the potential for blunt trauma injuries, especially in scenarios involving impacts with protective armor or blunt impactors. Jenerowicz et al. (2023) used the Abbreviated Injury Scale (AIS) to provide standardized terminology to describe injuries and rank injuries by severity. The BC of the PRIMUS and the numerical analysis of the GHBMC was compared to condition C of the Bir and Viano (2004) study. Figure 21 shows a comparison of the BC with the probability of an AIS 2 or 3 injury occurring. The study concluded that there was good agreement between the numerical simulations and the experimental ATD tests. However, when compared to the PMHS data (Bir et al., 2004), discrepancies were noted likely due to different experimental conditions (i.e., velocity) and differences in mass and diameter of the impactor.

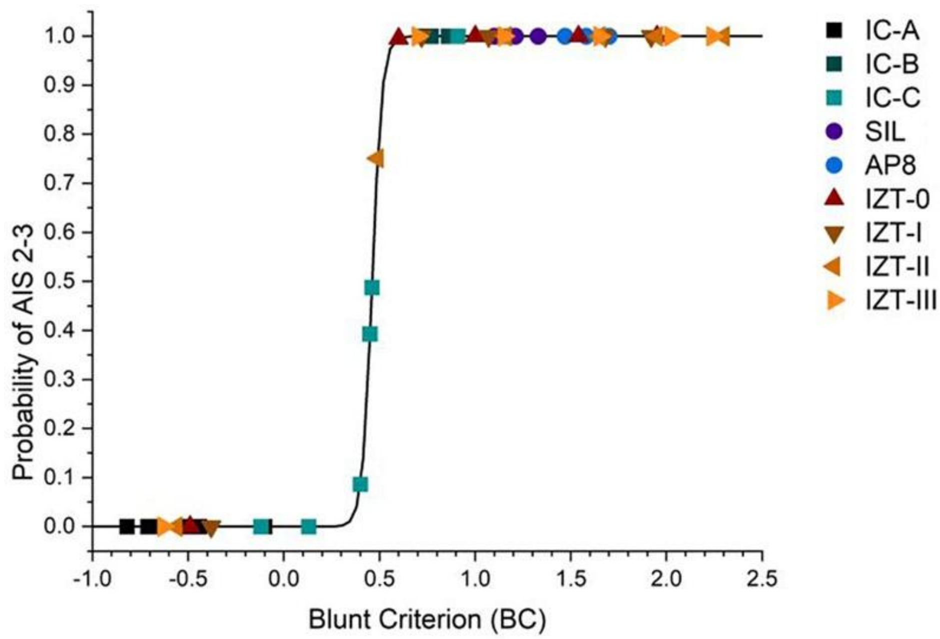

Figure 21. Blunt criteria (BC) calculations with probability of AIS 2 or 3 injury were compared to results from the Bir and Viano (2004) study: PRIMUS thorax (target zones IZT-0 through III), the numerically determined values on the GHBMC M50 (substitute impactor layers SIL and AP8) by Jenerowicz et al. (2023), and real PMHS data (impact conditions A, B, and C [IC-A through C]) by Bir and Viano (2004). Figure reproduced with permission from Jenerowicz et al. (2023).

Another limitation noted in the study included the failure of accelerometers at high impact velocities and the need to critically evaluate the methods used for calculating the BC, as current methods might not fully capture the effects of protective components. However, the authors suggested continuing research to validate and refine BABT evaluation methods.

Chaufer, M., Delille, R., Bourel, B., Maréchal, C., Lauro, F., Mauzac, O., & Roth, S. (2024b). The use of human surrogate for the assessment of ballistic impacts on the thorax. *Dynamic Behavior of Materials, 1*, 121–128.

The research by Chaufer et al. (2024b) explored the development and validation of Surrogate Hermaphrodite Universal Body YX (SurHUByx) (Figure 22), a physical surrogate designed to emulate the biomechanical response of the human thorax to non-penetrating blunt ballistic impacts. The HUByx finite element model (FEM) was adapted to form the SurHUByx FEM, which involved simplifying the anatomical and material complexities of the original model to ensure it was feasible for physical construction using commercially available materials. This numerical model served as the foundational blueprint for a reverse engineering process to construct the physical SurHUByx. The physical surrogate was crafted to mimic the anatomical and mechanical properties of the human thorax. Materials included polyurethane resin for bones, a gel based on styrene-ethylene-butylene-styrene (SEBS) for internal organs and muscle, and vinyl for the skin. All components were assembled using advanced molding and casting techniques.

Figure 22. The SurHUByx surrogate skin could be removed to adjust the impact location (red dot). Figure reproduced with permission from Chaufer et al. (2024b).

The consistency of the surrogate response regarding corridors and sternal fracture was validated using controlled non-penetrating ballistic impact tests on the SurHUByx torso model that primarily focused on the mid-sternum area (Figure 22). Researchers at Interdisciplinary Laboratory Carnot of Bourgogne aimed to replicate the same non-penetrating ballistic impact conditions (A, B, and C) used by Bir et al. (2004) noted in Table 1. Condition A included a 140 g impactor launched at 20 m/s, condition B included a 140 g impactor launched at 40 m/s, and condition C included a 30 g impactor launched at 60 m/s. The impactors used were rubber baton L5A7 impactors and were launched with a pneumatic launcher. For the data analysis, displacement and force versus time curves were plotted and VCmax was calculated. Lastly, the biofidelity of the surrogate was compared to existing biomechanical corridors from PMHS experiments (Bir et al., 2004).

Impact results from the SurHUByx surrogate were in the upper range of the displacement-time corridors for conditions A and C, and the middle of the corridor for condition B (Figure 23). Impact results from the SurHUByx surrogate were in the lower range of the force-time corridors for conditions A and B and the upper part for condition C (Figure 24). Regarding VCmax values, for condition A, SurHUByx showed a higher VCmax than the corridors. For conditions B and C, VCmax values were on the upper range of the corridors (Figure 25).

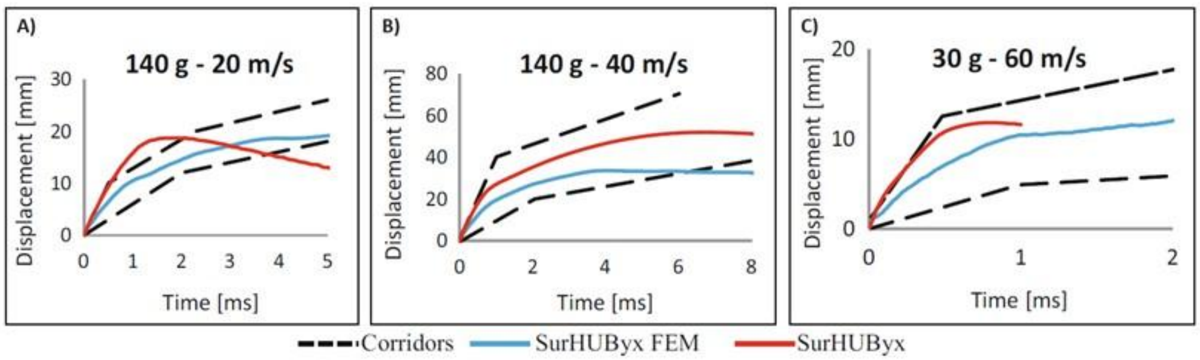

Figure 23. Displacement-time curves were created for impact conditions (A, B, and C). Figure reproduced with permission from Chaufer et al. (2024b).

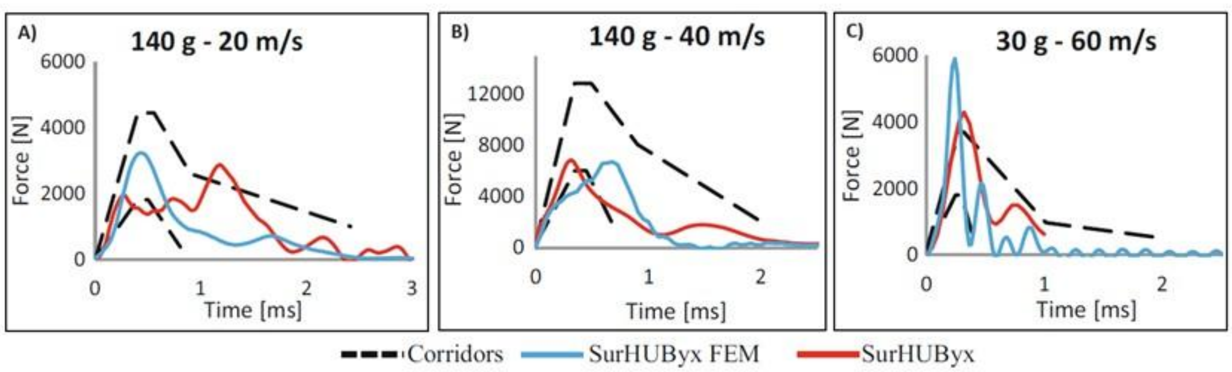

Figure 24. Force-time curves were created for impact conditions (A, B, and C). Figure reproduced with permission from Chaufer et al. (2024b).

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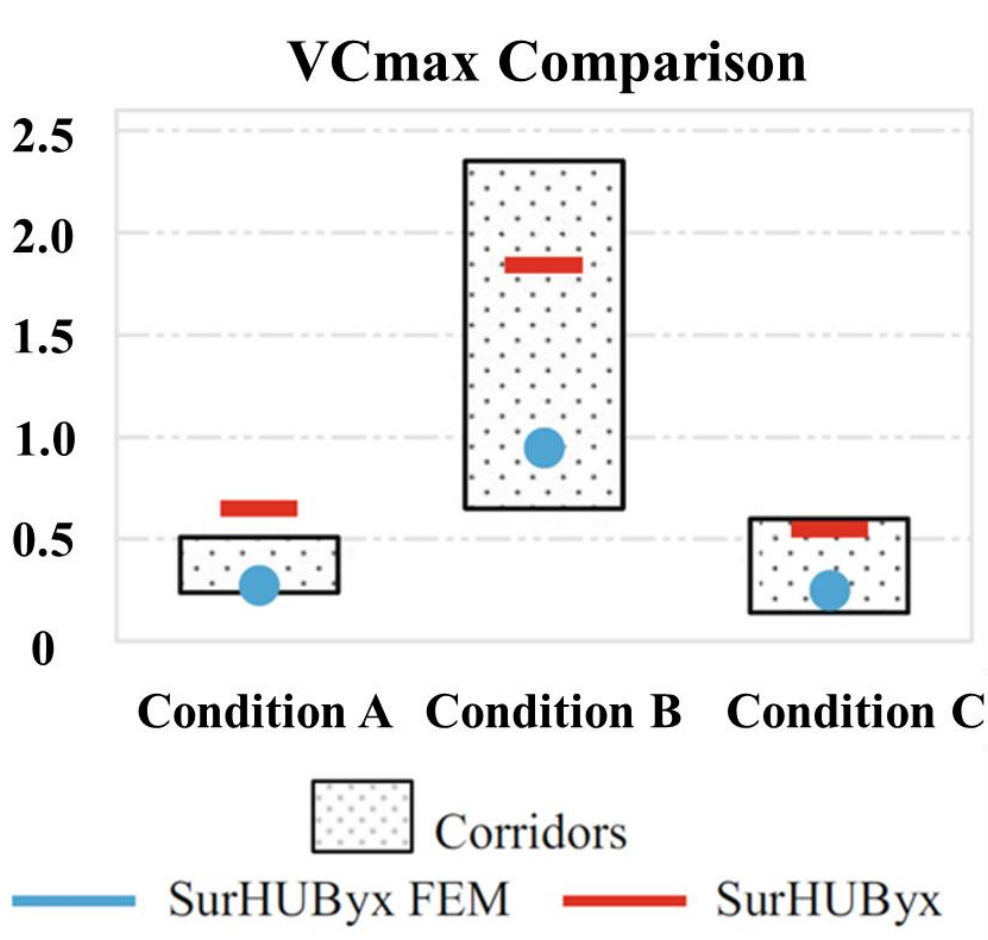

Figure 25. VCmax was compared between PMHS experiments, SurHUByx, and SurHUByx FEM for each impact condition. Figure reproduced with permission from Chaufer et al. (2024b).

Findings from these experiments highlighted the ability of SurHUByx to provide biofidelic responses to non-penetrating ballistic impacts. Researchers identified areas for refinement, particularly the further characterization of SEBS gel-based materials used in muscle and mediastinum components to minimize disparities with the SurHUByx FEM. Researchers also indicated that integration of internal sensors within surrogate organs could enhance the assessment of injury criteria.

Limitations addressed in the study included discrepancies observed in rebound behaviors between the SurHUByx surrogate and SurHUByx FEM, highlighting the need for ongoing refinement and validation studies with active human thorax behavior to better understand and replicate real-time thoracic responses. The authors did not provide suggestions on surrogate improvement; however, they suggested that future efforts should involve the addition of sensors to the surrogate organs and simulate field impact scenarios to develop injury probability functions for each organ. In conclusion, the research demonstrated SurHUByx as a viable surrogate model for evaluating blunt impacts on the thorax; however, further evaluation is necessary to determine the compatibility with armor systems and its ability to withstand live-fire rounds, as the current testing was conducted with baton impacts only.

Summary of Results

A summary of the data from this non-penetrating blunt ballistic trauma literature review is presented in Table 5 and Table 6. These tables provide a comprehensive overview of the impactors, velocities, and impact locations used by researchers to investigate the human response to high-velocity impacts.

Table 5. Summary of Impactor Parameters, Impact Location, and Biofidelic Corridor Development for Each Study with the Surrogate Protected by Armor

Source	Impactor	Mass (g)	Velocity (m/s)	Calculated Kinetic Energy (J)	Impactor Diameter (mm)	Impact Location	Biofidelic Corridor Development
Bass et al. (2006)	7.62 mm NATO ball round	9.72	670 to 800	2,181.7 to 3,110.4	7.62	Sternum	PMHS data collected, but corridors not developed
Roberts et al. (2007)	22 caliber bullet	2.6	329	140.7	5.69	Sternum and liver	No
	9 mm bullet	8	332	440.9	9		
			358	512.7			
			430	739.6			
Bolduc and Anctil (2010)	Various	5 to 378	10 to 154	0.3, 59.3 to 18.9, 4482.3	18 to 97	Sternum	No
Shewchenko et al. (2020)*	PVC baton	140	40	112	37	Sternum	Used Bir et al. (2004) corridors
		48	60	86.4		Abdomen (epigastric)	Used Bir and Eck (2005) corridors
	Lacrosse ball	215	27	78.4	65	Cardiac silhouette	Used Dau (2012) corridors
Jenerowicz et al. (2023)	Polycarbonate impactor	9	57 to 193	14.6 to 167.6	19.9	Sternum	No

*Impactor was not specified, but Shewchenko et al. (2020) assumed a baton like Bir et al. (2004) due to lack of information.

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Table 6. Summary of Impactor Parameters, Impact Location, and Biofidelic Corridor Development for Each Study with the Surrogate Unprotected

Source	**Impactor**	**Mass (g)**	**Velocity (m/s)**	**Calculated Kinetic Energy (J)**	**Impactor Diameter (mm)**	**Impact Location**	**Biofidelic Corridor Development**
Bir (2000)	PVC baton	140	20	28	37	Sternum	Yes
			40	112			
		30	60	54			
Bir et al. (2004)	PVC baton	140	20	28	37	Sternum	Yes
			40	112			
		30	60	54			
Bir and Eck (2005)	PVC baton	45	60	81	37	Abdomen (epigastric)	Yes
Dau (2012)	Lacrosse ball shaft	188.4	13.4	16.9	64	Cardiac silhouette	Yes
			17.9	30.2			
		214.5	22.4	53.8			
			26.8	77			
Sedberry and Foley (2019)[□]	N/A	N/A	N/A	N/A	N/A	N/A	No
Yan et al. (2020)	Rubber ball	N/A	85	N/A	16	Sternum	No
			115	N/A			
			135	N/A			
Chaufer et al. (2024b)[◊]	Rubber baton L5A7	140	20	28	36.5	Sternum	Used Bir et al. (2004) corridors
			40	112			
		30	60	54			

[□]While testing was not completed, this study is listed for completeness of this literature review.
[◊]L5A7 is typically a plastic material; "rubber," as reported in the paper, may be inaccurate.

This review identified three studies that generated biofidelity corridors from PMHS testing (Table 7). All three studies utilized impactors fitted with accelerometers and employed high-speed video (HSV). Bir et al. (2004) and Dau (2012) used the HSV to measure the deflection; however, Bir and Eck (2005) did not detail their deflection calculation methods. Key variations existed between test methodologies included impactor launch methods, specimen suspension techniques, instrumentation, HSV data acquisition, and impact locations (Table 8). HSV recording rates and filtering methods also differed across the studies.

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Table 7. Summary of Studies with Biofidelity Corridor Development

<table>
<tr><th>Source</th><th>Impactor</th><th>Mass (g)</th><th>Velocity (m/s)</th><th>Kinetic Energy (J)</th><th>Impactor Diameter (mm)</th></tr>
<tr><td rowspan="3">Bir et al. (2004)</td><td rowspan="3">PVC baton</td><td rowspan="2">140</td><td>20</td><td>28</td><td rowspan="3">37</td></tr>
<tr><td>40</td><td>112</td></tr>
<tr><td>30</td><td>60</td><td>54</td></tr>
<tr><td>Bir and Eck (2005)</td><td>PVC baton</td><td>45</td><td>60</td><td>81</td><td>37</td></tr>
<tr><td rowspan="4">Dau (2012)</td><td rowspan="4">Lacrosse ball shaft</td><td rowspan="2">188.4</td><td>13.4</td><td>16.9</td><td rowspan="4">64</td></tr>
<tr><td>17.9</td><td>30.2</td></tr>
<tr><td rowspan="2">214.5</td><td>22.4</td><td>53.8</td></tr>
<tr><td>26.8</td><td>77</td></tr>
</table>

Table 8. Comparison of Testing Parameters between Bir et al. (2004), Bir and Eck (2005), and Dau (2012)

Source	Impactor Launch Methods	Impactor Accelerometer	HSV Recording Rates	Impact Location
Bir et al. (2004)	Ballistic air cannon	Custom made Entran Model EGAXT, 10K	6,000 to 9,000 frames per second (fps)	Sternum
Bir and Eck (2005)	Ballistic air cannon	Endevco Model 7270, 20K	20,000 fps	Abdomen
Dau (2012)	Compound bow	Endevco Model 7270, 20K	10,000 fps	Heart

The biofidelity corridor comparisons generated from the three studies reveal distinct response differences (Figure 26). It was noted that the biofidelity corridors developed by Dau (2012) had lower loading onset rates, lower peak force levels, and greater deformations than the corridors developed by Bir et al. (2004) and Bir and Eck (2005). Lastly, the force-deflection corridors were separated by parameter (Figures 27 through 29) to allow for a clearer understanding of the response differences.

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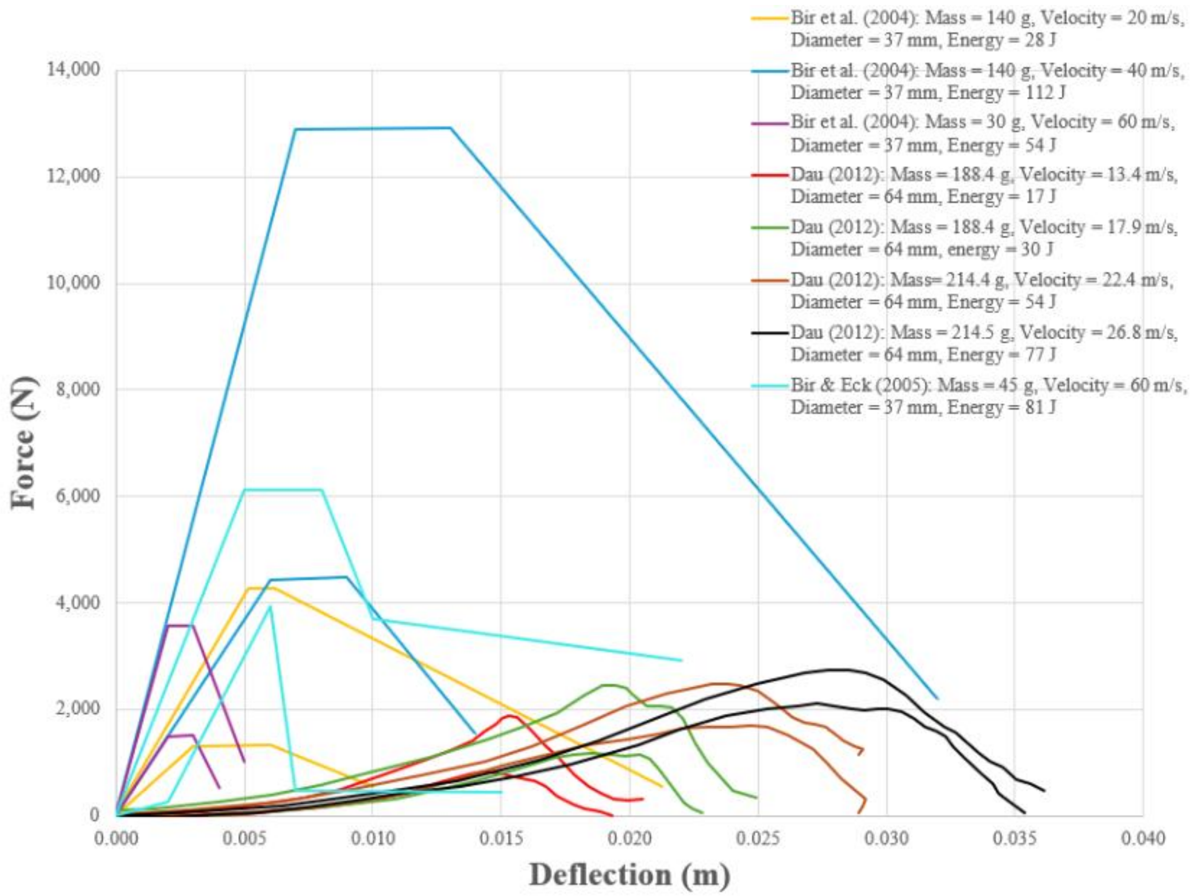

Figure 26. Force-deflection corridors for PMHS were derived from Bir et al. (2004), Bir and Eck (2005), and Dau (2012).

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While Bir et al. (2004) and Bir and Eck (2005) conducted tests that employed a 60 m/s impact velocity (Figure 27), the Bir and Eck (2005) tests used a 15 g heavier impactor which resulted in a 50% increase in impact energy. Consequently, Bir and Eck (2005) reported greater deflections into the tissue and a higher impact force as calculated from the indenter-mounted accelerometer data.

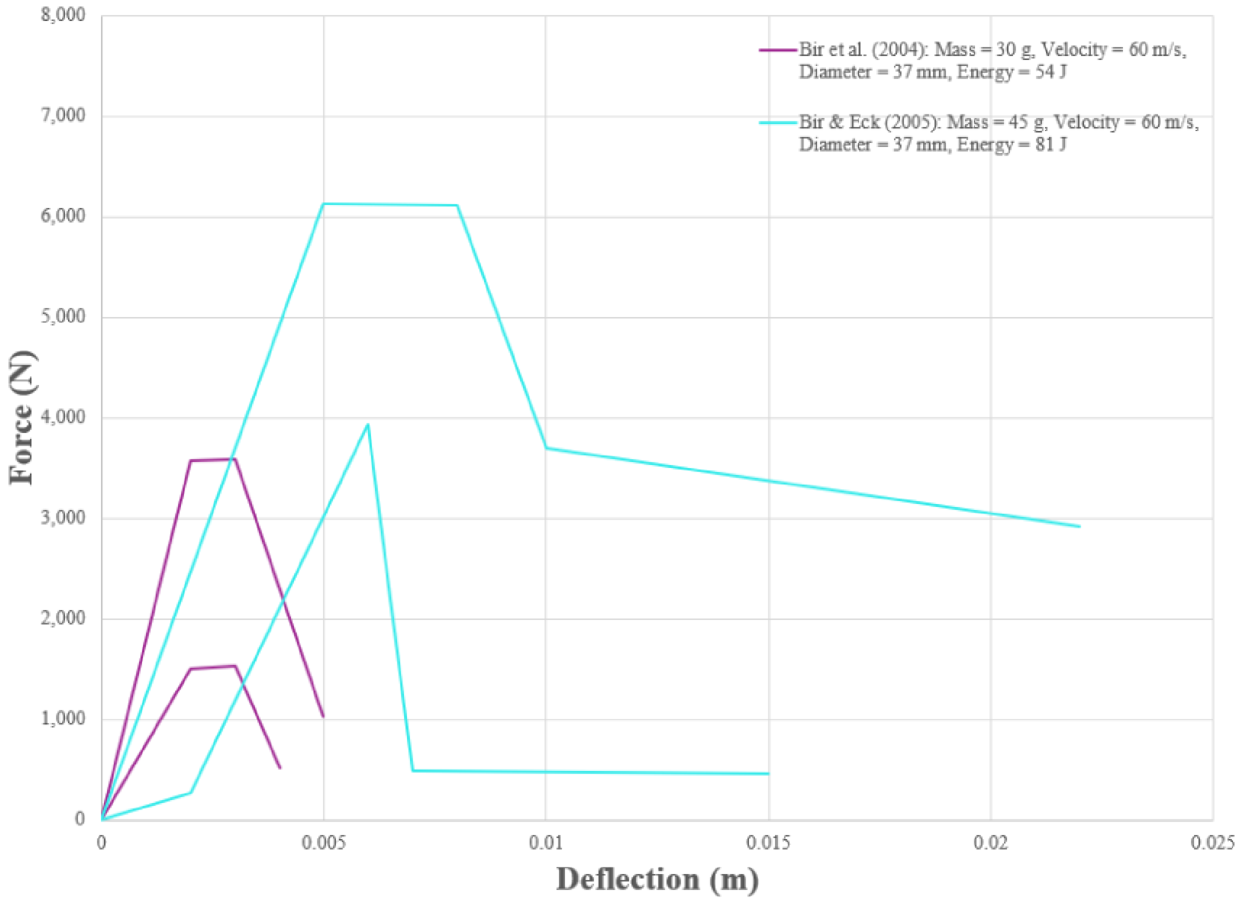

Figure 27. Force-deflection corridors for PMHS were derived from Bir et al. (2004) and Bir and Eck (2005) under similar impact velocities of 60 m/s but with different impactor masses, 30 and 45 g, respectively.

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Both Dau (2012) and Bir et al. (2004) conducted tests at 54 Joules (J) of impact energy (Figure 28); however, Dau (2012) reported a lower peak force and greater deflection. While the energy was constant, the impactor shapes, masses, and velocities were drastically different. This response discrepancy persists even when considering comparable impact velocities and energies (approximately 20 m/s and 30 J), resulting in Dau (2012) experiencing substantially greater deflections and a peak force roughly half that of Bir et al. (2004) (Figure 29).

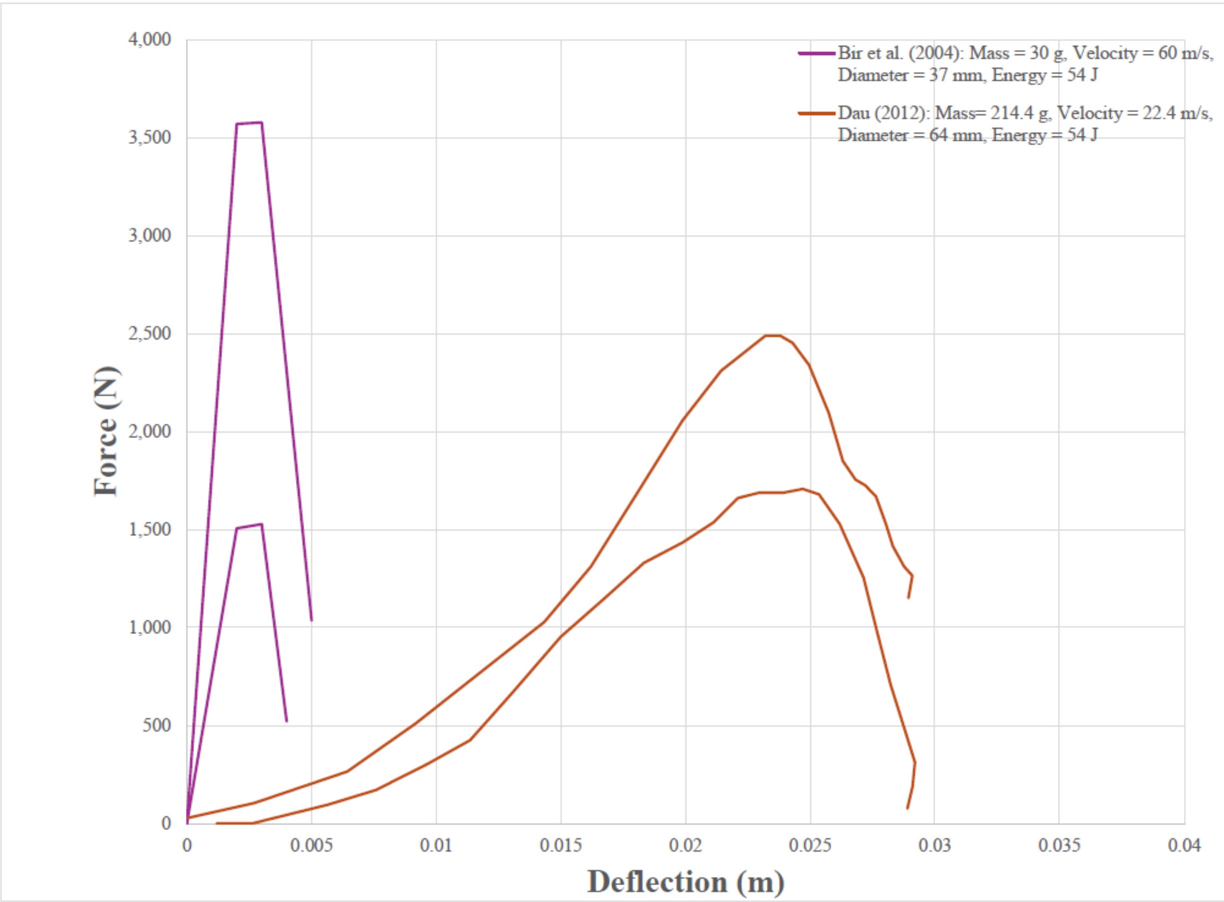

Figure 28. Force-deflection corridors for PMHS were derived from Bir et al. (2004) and Dau (2012) under similar impact energies of 54 J.

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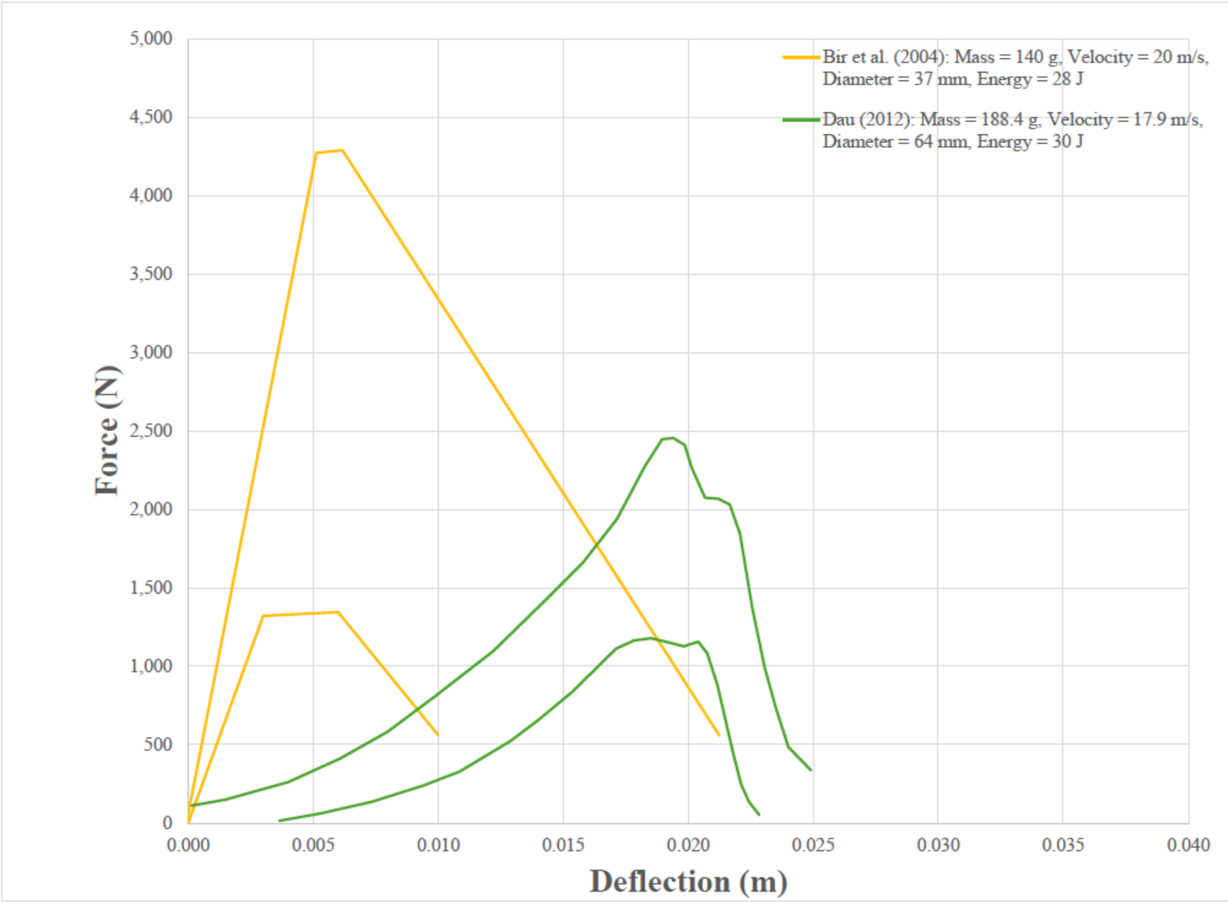

Figure 29. Force-deflection corridors for PMHS were derived from Bir et al. (2004) and Dau (2012) under similar impact velocities and energies of 28 m/s and 30 J, respectively.

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Discussion

The development of a biofidelic surrogate capable of accurately replicating human thoracic responses is important for detailed injury prediction. Achieving this biofidelity depends on a complex combination of variables, including the anatomical location being simulated (e.g., thorax, abdomen), impactor characteristics (shape, mass, velocity), and the specific materials and construction of the surrogate itself. Historically, despite its lack of biofidelity, RP1 clay has been used as the surrogate by the military, NIJ, and the body armor industry to measure BFD for the risk assessment of non-penetrating blunt ballistic impacts on the human body (Bolduc & Anctil, 2010; Shewchenko et al., 2020). Bir et al. (2004) reported that velocities above 250 m/s were associated with ballistic ammunition being fired into body armor, whereas the 20 to 250 m/s range was more representative of the blunt BFD impact velocity resulting from armor-defeating ballistic threats. This literature review identified 12 studies where researchers conducted testing with non-penetrating ballistic impacts; however, only three of the identified studies developed biofidelic corridors using velocities associated with blunt BFD impact. It is notable that after almost two decades, Shewchenko et al. (2020) and Chaufer et al. (2024b) still cited the Bir et al. (2004) corridors in their recent work.

Variances in testing methodologies across the Bir et al. (2004), Bir and Eck (2005), and Dau (2012) studies preclude definitive conclusions about the similarities between the biofidelity corridors produced. The researchers used a wide range of velocities for testing, which made it difficult to ascertain which parameter had the largest influence on corridor development. A comparison of the Bir et al. (2004) and Bir and Eck (2005) corridors, which were developed with the same impactor velocity, shape, and diameter (Figure 27), showed that the initial slope of their force-deflection curves were similar. The similar initial response of the two corridors in Figure 27 indicated that velocity influences the measured responses from the impacts. The higher peak force in Bir and Eck (2005) could have stemmed from the higher kinetic energy of the impactor or the difference in impact location (Figure 27). This is further illustrated in Figure 28 where the Bir et al. (2004) and Dau (2012) corridors developed from tests with different velocities were compared. The initial slope of the corridor developed by Bir et al. (2004) was notably steeper in the force-deflection graph at a velocity more than twice that of the corridors developed by Dau (2012).

Additionally, the diversity of the impactor types and masses made it difficult to compare the biofidelity corridors because the use of impactors made from different materials, with different shapes, and various sizes influenced biomechanical response. Bir et al. (2004) and Bir and Eck (2005) used a PVC baton impactor with a flat impact surface while Dau (2012) used a lacrosse ball with a diameter almost twice as large as the PVC baton. These differences in impactors could account for the differences in biofidelic response noted on the force-deflection corridors (Figure 26; Figure 28 and 29). Additionally, lacrosse balls have a coefficient of restitution requirement of 0.6 to 0.7, which allows the ball to deform and store energy during impact (National Operating Committee on Standards for Athletic Equipment [NOCSAE], 2020). Dau (2012) acknowledged that the lacrosse ball was less stiff than the PVC impactor used to create the Bir et al. (2004) corridors. This difference between impactors could also account for the different biological responses of the specimens. There must be consistency of impactor type, mass, and geometry during testing to provide comparable biofidelity data.

Furthermore, the comparison of Bir et al. (2004), Bir and Eck (2005), and Dau (2012) in Figure 26 may stem from variations in intended use case, experimental setup, and data collection methods across these studies. In general, there is a need for more standardization in how data are collected, but especially within similar impact environments. For example, blunt ballistic impact studies such as Bir et al. (2004) and Bir and Eck (2005), exhibit variations in accelerometers, data acquisition systems, and HSV frame rates (Table 8). Additionally, Bir et al. (2004) and Bir and Eck (2005) used a flat face, right angle cylinder to investigate the effects of non-penetrating blunt ballistic impacts while Dau (2012) used a spherical shaped impactor to study the risk of injury associated with lacrosse ball impacts. The differences in biological response seen in Figure 26 demonstrate why biofidelity data need to be collected for conditions representative of the intended environment. The biofidelity corridors identified in this review may not be appropriate to assess BFD when an armor system successfully defeats a kinetic threat. Surrogates must be developed with the conditions representative of the intended environments to ensure accurate injury risk assessment. Given the substantial differences in biofidelic corridors found in this review, using these data to develop a surrogate for BABT is not prudent. Opportunities exist to generate new corridors from existing blunt ballistic impact research, such as the PMHS data collected by Bass et al. (2006); however, further research with applicable loading conditions is needed to explore additional anatomical regions to develop more comprehensive biofidelity corridors.

A consortium of research experts is working to develop region-specific injury criteria for blunt insults characteristic of BABT events. Some of the data collected during their research can be used to define human biofidelity and fill the existing knowledge gaps surrounding the thoracic response to non-penetrating blunt ballistic trauma. Preliminary studies characterized various locations in the thoracoabdominal region (such as the liver, lung, and cardiac regions of the thoracic cavity) and demonstrated that the tissue response from blunt impacts differed due to the diverse amount of muscle mass, presence of skeletal structures, and presence of various organs (Yoganandan, Shah, et al., 2024; Kote et al., 2024; McMahon et al., 2025; Yoganandan et al., 2025). Preliminary research has shown that the size and shape of the impactor significantly affect the biomechanical response of the tissue in blunt impacts to the lung and liver (Yoganandan, Somasundaram, et al., 2024). The influence of impactor design on tissue response highlights the need to assess the metrics used to describe the tissue response that will account for such variability. For instance, the VCmax value, which was reported in several studies (Bir, 2000; Bir & Eck, 2005; Bolduc & Anctil, 2010; Chaufer et al., 2024b; Dau, 2012), is not universally accepted because of the inaccuracy of the criterion at different ballistic rates (Chaufer et al., 2024b; Bass et al., 2006). However, initial findings from Yoganandan, Shah, et al. (2024) suggest that the VC, an injury criteria metric based on peak velocity and correlated to energy and momentum, is a more accurate predictor of injury than force or deflection. This is because the observed viscous response trend aligns more closely with changes in velocity than other parameters. The culmination of this research group's efforts will provide a foundation for extracting accurate thoracic biofidelity. Results from the regional thoracic blunt injury criteria research can be analyzed to develop biofidelity corridors to assess alternative surrogates, enabling the selection of an appropriate surrogate for BABT research efforts.

Conclusion

This review effectively identified the scarcity of published data in open literature on thoracoabdominal biofidelity under BABT loading conditions, highlighting the need for operationally relevant loading conditions (velocity, mass, impactor geometry) to establish consistent and reliable biofidelic corridors in specific anatomical regions. While Bir et al. (2004), Bir and Eck (2005), and Dau (2012) proposed thoracoabdominal biofidelity corridors with impacts of BABT relevant mass and velocity, their impactors were not operationally relevant to the BABT environment and thus influenced the measured biofidelity. Bir et al. (2004) and Bir and Eck (2005) used a flat impactor unsuitable for replicating armored impacts, while Dau (2012) used a lacrosse ball with inappropriate material properties for BABT. These limitations, in conjunction with methodological differences across the three studies, hinder direct comparison. Thus, additional region-specific biofidelity data are needed for specifying the performance of a BABT test surrogate with human-like responses. A BABT test surrogate with human-like responses would more directly enable the use of regional injury tolerance criteria to develop future body armor performance standards.

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