Experimental modelling of blunt ballistic impact on a male thorax surrogate: study of rib fractures and lung injuries predictions

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Abstract. Modelling of body injuries caused by non-penetrating ballistic impacts is a major challenge. Experiments on biological models are difficult to conduct due to ethical and logistical constraints and on the data that can be collected. These limitations can be overcome by using physical or numerical surrogates, but their results must be correlated with real injuries recorded by ballistic injury databases. The objective of this study is to establish injury prediction curves for rib fractures and pulmonary injuries based on the applied energy levels. Twenty ballistic impact scenarios from French and American reports were analysed. These cases were replicated using a physical and biofidelic thoracic surrogate, SurHUByx. The surrogate used represents the torso of a 50th percentile male and it is designed to replicate the biomechanical responses of the human body to ballistic impacts. SurHUByx is equipped with different sensors on the ribs and in the lungs measuring deformations and pressures during impacts. The data collected were then analysed, retaining only the maximum value for each internal organ. A normalisation process adjusted the data according to body mass index to account for individual variability. Then, a regression model was used to analyse the relationship between injury probability and sensor values. The optimal injury diagnosis threshold was determined to use the Youden method, prioritising the reduction of false negatives. The results enabled the calculation of injury probability based on sensor data. This study highlights the interest of sharing ballistic injury cases to constitute a more reliable database. It also highlights the use of surrogates to replicate cases and develop injury prediction models.

1. INTRODUCTION

Law enforcement officers and military personnel are exposed to the threat of ballistic injuries in occupational situations [1]. To reduce these risks, protective equipment, such as bulletproof vests, are used. However, these do not guarantee absolute protection against injuries. Even in the absence of projectile penetration through the armour, ballistic impacts can still cause severe injuries, called Behind Armour Blunt Trauma (BABT). These injuries result from the interaction between impact energy and dynamic deformation at the back of the bulletproof vest [2].

Currently, Roma Plastilina N°1, an oil-based modelling clay, is the standard material for the evaluation of body armour. The armour is placed on the clay and impacted with test projectiles specified by the standard. Several impacts are made per panel. The acceptability of the results is determined based on one of two conditions: either each individual Back Face Deformation (BFD) measurement in this material not exceed 44 mm, or individual BFD values fall between 44 and 50 mm, and the average of all recorded impact measurements for a sample of the same model remains below 44 mm. Any measurement exceeding 50 mm is considered a failure [3].

The human torso is not a homogeneous structure, each region of the body responds differently to impacts, requiring specific studies for each area of interest. Modelling of injuries caused by non-penetrating ballistic impacts is a major challenge [4,5]. To address this issue, significant research has been carried out to better understand the effects of blunt impacts on the human body. Animals and Post Mortem Human Subject (PMHS) experiments are a classic method for assessing ballistic injuries [2,6]. However, ethical and logistical constraints severely limit these experiments, as do the difficulties associated with collecting and using the data obtained. These limitations can be overcome by using physical or numerical surrogates. Among these surrogates, Styrene-Ethylene-Butylene-Styren (SEBS)

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blocks are commonly used to assess the ballistic protection effectiveness [7,8]. Additionally, digital anthropomorphic surrogates such as the HUByx, SurHUByx FEM, ARL, and ATBM models are used [9-11], and physical surrogates such as "Gelman" [12] and "SurHUByx" [5]. The SurHUByx surrogate is specifically designed to represent the anthropometry of a 50th percentile male torso, facilitating the recreation and analysis of ballistic impacts. However, the data obtained from these surrogates must be correlated with real injury cases.

Thus, an experiment with the use of a male physical surrogate of average build is justified, in ordor to develop new injury criteria based on medical records from officers shot in the line of duty reports, and post test records from tests on PMHS. These criteria should account for the variability in injury risks across different regions of the torso.

In ballistics research, collecting BABT cases remains a major challenge. For experimental reproduction to be relevant, several parameters must be precisely known. Several studies have already reported recreations of cases in the literature [5,13,14]. Given the difficulty of grouping these cases, the physical build of individuals described was not a criterion for exclusion. Therefore, standardisation based on Body Mass Index (BMI) was conducted to minimise these differences.

The objective of this study is to establish injury risk curves for rib fractures and lung injuries as a function of the applied energy levels. The development of these risk curves will allow for modelling of the relationship between the probability of injury and the impact applied.

This study aims to use a physical surrogate to recreate ballistic impact scenarios from French and American reports of law enforcement officers who were shot in the line of duty. Case reports were analysed and grouped. Only cases involving a thoracic ballistic impact occurring in the sagittal plane of a male individual were retained. Missing data necessary were identified. Then, the different cases obtained were recreated on the physical surrogate under conditions identical to those described in the case report. Exemplar bulletproof vests were used to ensure the vest model was the same as what was reported in the cases, as well as the projectiles specified in the reports. Finally, the standardisation of the data with respect to the BMI of average male was carried out on the data in order to perform a statistical processing of the data to generate injury probability curves corresponding to a male of the 50th percentile.

2. MATERIAL AND METHODS

The following section outlines the ballistic recreation cases forming the basis of this study, the experimental methods employed, the data processing procedures, and the overall experimental evaluation approach. In addition, the normalisation of data relative to the size of a 50th percentile male for result assessment is discussed and the principles used to construct risk curves are presented.

2.1 Case reports

In this study, ballistic impact scenarios described in French and American BABT injury reports were analysed. The objective was to gather relevant data to reproduce these situations under experimental conditions. Key information included physical subject characteristics, the type and model of bullet-resistant vest worn, precise impact locations, injury descriptions, weapons, and projectiles, including their velocities. In order to minimise variability among the cases studied, the analysis focused on impacts involving the thoracic region of male subjects. The collected data were organised into Table 1, which summarises the selected cases, including subject characteristics and identified injury types. In each case, a lesion value was assigned as 0 when no lesion was observed on the studied organ and 1 when a lesion was present. Additionally, Figure 1 illustrates the location of bullet impacts relative to the ribs, as mentioned in different medical records. Each number corresponds to the case detailed in Table 1.

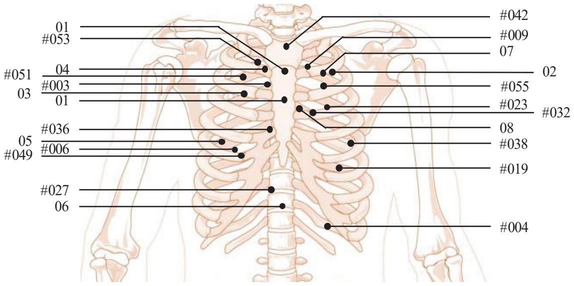

Figure 1. Location of impacts relative to the ribs

Table 1. Characteristics of individuals and their lesions

Case reference	Case reports type	Subject characteristics		Projectile	Impact velocity [m/s]	Body armour		Rib Fractures	Lung Lesion	Additional information
		Height [m]	Weight [kg]							
BABTID #003 [14]	US case	1.73	72.5	Lawman 9 mm 124 gr FMJ (Full Metal Jacket)	315	Second Chance	Monarch 329-MON-II	0	0	-
BABTID #004 [13]	US case	-	-	Remington .40 calibre S&W 180 gr	301	Second Chance	Ultima SMU-II + 001221	1	0	9th rib fracture
BABTID #006 [14]	US case	1.75	74.5	Lawman 9 mm 124 gr FMJ	356	Second Chance	MON-II + LSC	0	0	-
BABTID #009 [13]	US case	1.80	88.45	RWS .38 special 158 gr FMJ	263	PACA	KSG IIIA	0	0	-
BABTID #019 [14]	US case	1,75	-	Speer 9 mm 115 gr HP (Hollow Point)	366	ABA	XT2-1	1	0	8th rib fracture
BABTID #023 [14]	US case	-	-	American Eagle 9 mm 124 gr FMJ	355	ABA	XT2-2	0	0	-
BABTID #027 [13]	US case	-	-	Winchester .357 mag JHP (Jacketed Hollow Point)	379	ABA	SII-6.0	0	0	-
BABTID #032 [15]	US case	1.85	113.4	.38 calibre	296	ABA	XT3A-2	0	0	-
BABTID #036 [14]	US case	1.83	100	Winchester .45 calibre, 230 gr, FMJ	250	Safariland	GX-II.0	0	0	-
BABTID #038 [13]	US case	1.70	63.5	.38 calibre, FMJ	259	Safariland	SII-6.0	0	1	Underlying pulmonary contusion in anterior left lower lobe
BABTID #042 [14]	US case	1.65	64	Federal Premium .40 calibre S&W 180 gr HP	305	Point Blank	CIIA-1	0	1	Bruised lungs
BABTID #049 [14]	US case	1.90	100	Winchester .45 calibre 230 gr JHP	243	ABA	XT3A-2	0	0	-
BABTID #051 [14]	US case	1.87	131.5	12 gauge	406	Monarch	SUM IIA R02 6010	0	1	Pulmonary contusion
BABTID #053 [13]	US case	1.88	70.31	Lawman 9 mm 124 gr TMJ (Total Metal Jacket)	322	Safariland	BA-2000S-SM01	0	0	-
BABTID #055 [13]	US case	1.85	68.04	Winchester .357 mag JHP	374	Safariland	BR01	1	0	2nd and 4th rib fracture
01	PMHS case	1.74	72	calibre 12 Brenneke	385	CDX 2x10 layers		1	0	6 rib fractures
02	PMHS case	1.77	50	calibre 12 Brenneke	435	CDX 2x10 layers		1	0	1 rib fracture
03	PMHS case	1.65	52	Gévelot 9 mm Para. 8.18g	378	CDX 10 layers		0	0	-
04	PMHS case	1.60	47	Gévelot 9 mm Para. 8.18g	370	CDX 20 layers		0	0	-
05	PMHS case	-	51	Gévelot 9 mm Para. 8.18g	373	CDX 20 layers		0	0	-
06	French case	-	-	COP (Cartouche Opérationnelle de Police) 9 mm Parabellum HP	328	PN2002		0	0	-
07	French case	1.76	80	.38 calibre special JHP	250	COMODITEX GN 2001		0	0	-
08 [16]	Bibliographic reference	-	-	FlashBall	120	-		0	1	-

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2.2 Anthropomorphic surrogate

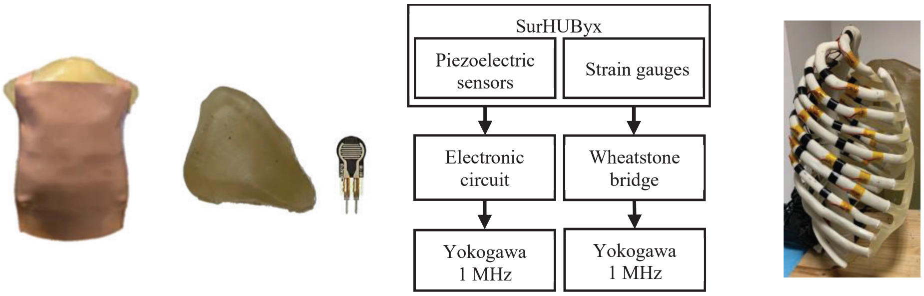
This study aims to recreate BABT cases by an experimental approach. A surrogate, previously designed and validated, which allows for the development of injury risk curves. In this context, SurHUByx was used.

2.2.1 SurHUByx features

The SurHUByx physical surrogate was used to represent the torso of the 50th percentile male (Figure 2a). It was designed to replicate the biomechanical responses of the human body to ballistic impacts. The surrogate was composed of various materials specific to anatomical regions, allowing for a realistic reproduction of human physical characteristics. The external layer simulating skin was made of vinyl. The muscle tissue, the mediastinum, and vital internal organs, such as heart, lungs, liver, and spleen were replicated using SEBS gel with different concentrations as previously described. The skeletal structure is constructed from a two-component resin, and the costal cartilage was made from an elastomeric resin. SurHUByx was equipped with sensors placed on the ribs and within the lungs to measure deformations and pressures during ballistic impacts [5].

2.2.2 SurHUByx instrumentation

Strain gauges were installed on the ribs (Figure 2d). Gauges had a sensitivity of 3% with a resistance of 350 Ω. All data were recorded at a sampling rate of 1 MHz using a Yokogawa DL750 recorder oscilloscope. Fifteen gauges, positioned on the ribs, close to the impact zone, were connected to the oscilloscope. Piezoelectric pressure sensors, placed at the centre of the internal organs, measured the pressure generated during the impacts (Figure 2b). These uniaxial sensors required frontal shooting tests to ensure reliable data. The activation sensitivity of these sensors was approximately 0.2 N. Figure 2c illustrates the acquisition schema used to collect specific information about the ribs and internal organs.



(a) (b) (c) (d)

Figure 2. SurHUByx (a) Piezoelectric sensors used in internal organs (b) SurHUByx data acquisition chain (c) and strain gauges on the ribs (d)

2.2.3 Validation of SurHUByx in the ballistic field

The surrogate SurHUByx was used in this study to simulate ballistic impacts on the thoracic region. Specifically designed to replicate the response of the 50th percentile male thoracic response to ballistic impacts, its effectiveness in the ballistic domain has been validated [5]. The results presented in the study by Chaufer [5] are consistent with the experimental values reported by Bir [17]. These data validated the global behaviour of the SurHUByx thoracic surrogate during ballistic impacts.

2.3 Test protocol

Figure 3 shows the experimental setup used to recreate ballistic impacts on the SurHUByx surrogate. SurHUByx was positioned 7.5 m from the gun. Before each impact, a calibration shot was performed to ensure that the projectile was launched at the desired velocity to replicate the specific case. After aligning the intended point of impact using a laser sight, the projectile was fired at the surrogate. The projectile velocity was recorded using an IR velocity gate. The impact on the ballistic vest was captured by a high-speed camera (Phantom v2012) at a rate of 22,626 frames per second. The body armour and projectiles were consistent with the descriptions in the case reports. Due to the limited surface area available on the ballistic panels, each test case was replicated only once on the SurHUByx. To recreate a case, the same type of projectile specified in the case reports was used, along with bulletproof vest models models manufactured within five years of the one worn by the officer. Tests were conducted from the least severe to the more severe. A complete assessment of the surrogate was conducted between each impact to ensure its physical integrity. If any damage was detected on the SurHUByx surrogate, the necessary repairs were carried out before continuing the experimental tests.

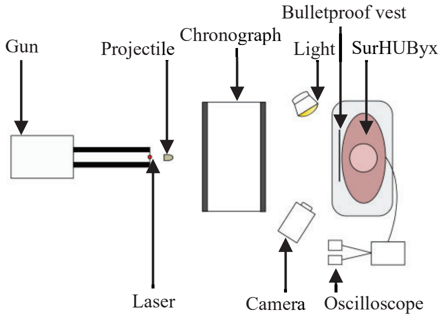


Figure 3. The setup of the experimental device

2.4 Data analysis

2.4.1 Extract data

For each case studied, only the maximum value recorded by each strain gauge was retained. Regarding the piezoelectric pressure sensors, the method was similar to that applied to the strain gauges. Only the maximum value of each sensor was retained, thus representing one datum per internal organ. For the lungs, the retained value was the highest of the two measurements. Thus, each datum obtained was associated with a lesion value: 0 if no lesion was observed on the organ studied or 1, if a lesion was present.

2.4.2 Data normalisation

In the case reports presented in Table 1, individuals had different physical characteristics in terms of mass and stature. These differences made the interpretation of the data more difficult. Given that, individual variations in these parameters influence the response of body structures to ballistic forces [18], a normalisation approach was carried out. Thus, the data from each individual were adjusted according to the BMI of a 50th percentile male, with reference values of 77 kg for mass and 1.78 m for stature, as explained by Serre et al. [19]. BMI is used to assess the body composition of an individual, as defined by Equation 1. This approach made it possible to calculate a specific normalisation factor for each case (Equation 2) [20]. Once the factor was obtained, it was applied to the collected data by multiplying the data by the corresponding normalization factor. This method allowed to for normalise normalisation of the results, facilitating their interpretation. The trends are independent of the morphological characteristics of the individuals.

$$\text{BMI} = \text{Mass (kg)} / \text{Stature}^2\ \text{(m)} \qquad (1)$$

$$\lambda = \text{BMI}_{50\text{th}} / \text{BMI}_{\text{subject}} \qquad (2)$$

2.4.3 Creation of injury probability curves

The data were analysed using survival analysis to assess the relationship between the probability of injury occurrence and the value of an independent variable representing a technical parameter. In this study, the analysis was performed using MATLAB R2024b. The proposed approach was applied to establish risk curves for ribs and lung BABT resulting from ballistic impacts on the thorax. The International Organization for Standardization (ISO) has developed a step-by-step process for developing injury risk

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functions [21], providing a foundation for the use of a unified approach to constructing injury risk curves. This standard has been used in several previous studies [2,22].

The steps of the ISO approach are as follows: (1) data collection, (2) determination of censoring status, (3) verification of multiple injury mechanisms, (4) sample separation based on injury mechanisms, (5) estimation of distribution parameters, (6) identification of highly influential observations, (7) verification of the distribution hypothesis, (8) selection of the appropriate distribution, (9) validation of predictions against existing results, (10) calculation of 95% confidence interval, (11) evaluation of the quality index, and (12) recommendation of a curve per body region [21].

The 12 steps of the ISO procedure provide a structured approach, but they do not address all the nuances of the problem. Subsequent research has refined this process to bridge existing gaps [18]. The ISO approach did not provide a method for determining which biomechanical metric from the experiments was most correlated with injury outcomes. To address this, the selection process for the metric with the highest area under the curve (AUC) was proposed [22]. The Receiver Operating Characteristic (ROC) curve evaluates the discriminative ability of biomechanical variables the concerning injury outcomes. It is obtained by plotting sensitivity against 1-specificity for different classification thresholds. The AUC represents the predictability measure of metrics in terms of specificity and sensitivity. A higher AUC indicates a more predictive measure. The AUC was calculated for all potential criteria, and the metric with the highest AUC was selected for further analysis.

Once the best criterion was identified, survival analysis was conducted by plotting a Kaplan-Meier curve, a nonparametric method used to estimate the survival function. The inverse survival curve was analysed to illustrate the cumulative probability of injury. The parametric survival models studied were those recommended by the ISO standard. The fitted models included Weibull, log-normal, and log-logistic distributions. For each distribution, the Akaike Information Criterion (AIC) was computed to select the most suitable model.

To complement the evaluation of the model, an influence analysis of the observations was conducted using the DFbeta statistic. DFbeta measures the impact of each observation on the survival model coefficients. A high DFbeta value indicates a potentially influential observation.

Confidence intervals were then computed to quantify estimation uncertainty. The confidence interval 95% estimates a range in which the true parameter value is expected to lie with a given probability.

Finally, in order to determine the optimal threshold to maximise the effectiveness of injury diagnostic testing, the Youden index was applied. It is denoted as J (Equation 3). In this study, misclassification of a positive individual was considered more detrimental than that of a negative individual.

$$J = \text{Sensitivity} + \text{Specificity} - 1 \tag{3}$$

3. RESULTS

A total of 23 BABT impact tests were conducted on the SurHUByx surrogate, with all impacts located in the thoracic region. The output measurements from the sensors were normalised based on the BMI of the individuals. However, detailed individual characteristics were not consistently available in the case reports. Moreover, several reports did not specify whether lung injury was present, and cases where the impact occurred too far from the lung - and thus from the relevant sensor - were excluded.

To establish rib injury risk curves, 17 cases were considered. For pulmonary injury risk assessment, 12 cases were used. However, as there is only one case of injury in this study, generating risk curves for the lungs was not possible (Figure 4). The sample size across groups is uneven. Only one case represents the group “lesion”.

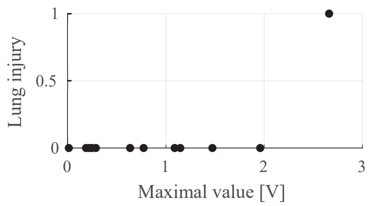

Figure 4. Lung data

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3.1 Normalised rib injuries predictions

Figure 5 illustrates the distribution of data based on whether a rib injury was reported in the case. The “No injury” sample has on average lower maximum strain values. It is 0.27% compared to 0.54% for the “Injury” sample. However, the sample size across groups is uneven.

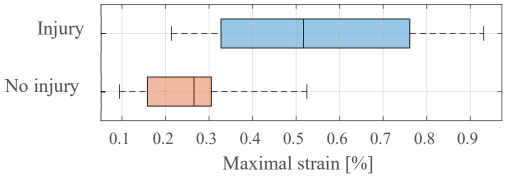


Figure 5. Boxplot for the normalised rib fracture data

The ROC curve was then plotted (Figure 6). The AUC for the maximum strain variable, after the data were normalising the data to BMI, was 0.7884. The decision threshold was determined to use the Youden index and the ROC curve. For the ribs, the threshold was 0.3462, with a specificity of 0.8462 and a sensitivity of 0.5.

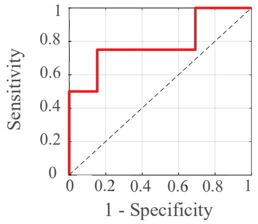
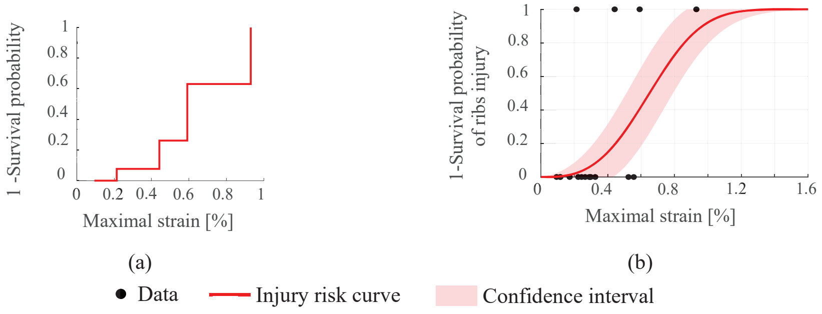


Figure 6. ROC curve of the ribs data

The Matlab routine output the inverse Kaplan-Meier survival curve (Figure 7a). Next, the three fitted models were plotted and analysed. Compared with the AIC value obtained in the analysis, the Weibull distribution was most appropriate in our study (Table 2). The risk of rib injury following a frontal ballistic impact is highlighted in Figure 7b which illustrates the results of the rib injury risk curve with the Weibull distribution. For a 50% risk of injury, the maximum rib strain was 0.65%.

Table 2. Injury risk curve final predictor and distribution selections with test statistics

Injury	Predictor	distribution	AIC
Ribs injury	maximum strain normalised with BMI	Log-normal	36.4
		Log-logistic	33.1
		Weibull	30.3



(a)

(b)

Figure 7. Survival curve (a) and best fit model injury risk curve for the ribs data (b)

4. DISCUSSION

One of the strengths of this study is the use of a physical surrogate for a male thorax to estimate the risk of certain BABT injuries. Using pressure transducers and strain gauges installed in the surrogate, experimental data were collected. These measured the stresses experienced during a ballistic impact on the SurHUByx. These data were then used for BABT injury probability analyses. However, generating distribution curves for the lung data was not possible. The inverse Kaplan-Meier survival curve had only one step (Figure 8), meaning that it cannot represent a Weibull, log-normal or log-logistic distribution. This limitation is due to the insufficient number of injury cases observed for this type of injury, making statistical estimates imprecise and the distribution curves unusable.

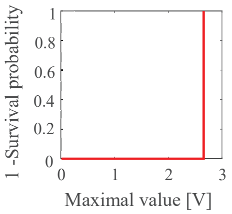


Figure 8. Survival curve

This experimental approach provided an ethical and reproducible alternative to testing on human or animal subjects [5]. However, the sensors integrated into the SurHUByx have certain limitations. For example, the sensors placed near the lungs are unidirectional and local, preventing accurate recording of impacts that do not occur in the sagittal plane. Furthermore, when an impact occurs at the tip of the lung, the distance between the sensor and the impact zone can lead to biased measurements.

The construction of injury risk curves from survival analysis is an approach widely used in the injury biomechanics [22] fields. These curves are beneficial, as they enable risk to be represented continuously as a function of an input variable [23]. This study draws on ISO recommendations and previous work [22] to establish injury risk curves. The approach adopted here aims to assess injury risks based on deformation predictions compared with observed injuries, in order to anticipate future injury probabilities.

Risk curves had already been established in the literature. McMahon et al. [2] assessed the risk of injury to the sternum, lungs and liver as a function of impact energy and penetration depth. Bass et al. [1] focused on the sternum (peak sternal impact), while Bir et al. [17] studied impact depth. However, comparison of risk levels with these studies is impossible due to the difference in the variables used. The SurHUByx does not allow quantification of the maximum depth reached on impact.

Next, the study took into account individual variability in case reports. The physical characteristics of the individuals mentioned in the reports were integrated with a scaling factor based on BMI. This BMI-based method seems to reduce morphology-related variations and reduce case exclusion. Chest depth was not used for normalisation, as suggested by the work of [17,24], as the data was not available from case reports. Normalised data from American and French ballistic reports was used to estimate the risk of rib injuries in men of average build. However, normalisation with BMI has certain limitations. For example, the mechanical properties of ribs vary according to an individual's size and morphology [25].

Finally, the collection of actual injury cases in the ballistics field remains difficult. The cases collected and analysed in this study constitute a significant database, with each reported case helping to refine BABT injury probability estimates. However, the total number of cases studied remains limited, particularly for lung injuries, where only one case of injury could be analysed in this study. This methodological weakness prevents the accurate modelling of a risk curve for this type of injury. A resampling approach, such as that proposed by DeVogel et al. [26] could be considered to balance the data classes and improve the robustness of the results.

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5. CONCLUSION

This study established injury risk curves for rib fractures following blunt ballistic impact, using the biofidelic surrogate SurHUByx. The study highlighted the correlation between measured strain levels and rib fracture probabilities from known BABT injury cases, validating the approach based on integrated sensors. However, the results of lung injuries remain limited due to the small number of injury cases. Nonetheless, the case presenting a lung injury corresponds to the one where the piezoelectric sensor signal was the most important, which indicates a potential interest in this instrumentation to detect this type of injury.

The integration of databases of real BABT events has helped to improve the reliability of predictive models, although constraints remain, notably in terms of the morphological variability of individuals. Standardisation of data by BMI has reduced these disparities.

The perspectives of this research include the expansion of the BABT database to establish injury risk curves for all vital organs. Furthermore, since this study was based exclusively on male subjects corresponding to the 50th percentile, future work will need to take into account morphological diversity, particularly that of women, in order to improve the representativeness of predictive models.

Acknowledgments

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