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# Rib fractures prediction method for kinetic energy projectile impact : from blunt ballistic experiments on SEBS gel to impact modeling on a human torso FE model

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## A B S T R A C T

The present paper aims to assess the risk of rib fractures caused by any rigid less-lethal kinetic energy projectiles. To that end, a coupled experimental and numerical approach is proposed to relate ballistic experiments with the risk of blunt trauma. A polymer gel block is employed as ballistic testing medium to interpret ballistic impacts through the measurement of the dynamic gel wall displacement. Moreover, a biofidelic 50th percentile human torso finite element model created in the code Hypermesh (Altair HyperWorks ©) is used to replicate experiments and real world accidents. Then, the probability curve of rib fractures is a function of the viscous criterion and derives from a study on human cadaver mid-sternum available in the literature. Twelve impact conditions of rigid projectiles are applied to a SEBS gel block and are replicated on the human torso model mid-sternum. A statistical analysis is performed by virtue of a Spearman's correlation matrix in order to identify relations between experimental measurements and the viscous criterion evaluated numerically. The determination of both statistical significances and correlation coefficients results in several strong correlations between experimental measurements and the viscous criterion evaluated numerically. These relations imply the establishment of transfer functions between experimental metrics on the gel block (the maximum gel wall displacement and a gel wall displacement – rate of displacement based metric) and the probability of rib fractures. Finally, these correlations constitute a primary and an up-and-coming predicting tool for the risk of rib fractures.

Keywords:

Non-penetrating ballistic impact; Experimental testing; Human torso; Finite element modeling; Blunt trauma

## 1. Introduction

The last few decades have seen the ongoing increase in ballistic impact studies, aiming important application areas such as: medical, civilian or military. Understanding the human body response under non-penetrating ballistic impacts has become a subject of interest. Indeed, Less-Lethal Kinetic Energy projectiles (LLKE) have been adopted by many law enforcement agencies to incapacitate dangerous individuals. However, the open literature has referred numerous case reports describing injury patterns relating to the impact of such projectiles [1–5]. In fact, the use of rubber bullets and police bean bag has resulted in liver laceration and pulmonary contusion in some cases [3,5]. Another fact mentioned by de Brito et al. [2] is that 61% of police bean bag

rounds have been located in the human torso and 44%, specifically in the thorax. Therefore, many scientists have focused their research on this location including vital organs of the human being.

To obtain a better insight into ballistic blunt trauma, researchers have employed Post-Mortem Human Subjects (PMHS) as surrogates during ballistic impact experiments [6,7]. Even though the use of human cadavers points out some drawbacks as elderly subjects, ethical issues, alterations in biomechanical properties, it may constitute the most reliable surrogate. Indeed, despite anatomical similarities between human and anesthetized animal organs, human tolerance to impact can't be directly determined during ballistic impacts with animal models [8,9].

Bir et al. [7] have investigated the biomechanical response of human cadavers during the impact of rigid round LLKE projectiles to the mid-sternum. This reference study results in the establishment of biomechanical corridors in force-deflection-time useful for the development and validation of anatomical models. Moreover, an extended analysis of this study by Bir and Viano

[6] have lead to the curve of probability of an Abbreviated Injury Scale (AIS) score equal to 2 or 3 based on rib fractures. This injury curve is established as a function of the Viscous Criterion ( $VC_{max}$ ) defined by Viano and Lau [10]. This criterion corresponds to the maximum of the product of the chest wall velocity and chest compression expressed in percent of thorax depth. The extensive information and conclusions of this study may be exploited through experimental and numerical approaches to determine the wounding potential of any rigid LLKE projectiles impacting a human mid-sternum.

On the one hand, the undetermined geometrical and mechanical properties of projectiles require ballistic experiments on a physical model to interpret any impacts. The literature review of Humphrey and Kumaratilake [11] on anatomical modeling in ballistic impacts has pointed out several disadvantages of physical dummies employed in ballistic experiments [12–14]. Developing an accurate representation of human body and organs results in a complex and costly task. Moreover, local measurements of stress-strain at any locations of the physical dummy are not feasible. Therefore, these conclusions have encouraged the research of a practical and reliable physical model. Thus, a transparent soft synthetic material has been adopted by the French Ministry of the Interior as ballistic testing medium to analyze non-penetrating ballistic impacts. The polymer SEBS gel (styrene-ethylene-butylene-styrene) exhibits excellent properties, such as transparency, mechanical consistency, reproducibility and environmental stability [15–18]. Such easy handling properties are in contrast with those of ballistic gelatin commonly used as a soft tissue simulant in ballistic impact studies [19,20]. Then, the dynamic gel wall displacement caused by the projectile impact can be processed through high-speed imaging. Macroscopic data can be then investigated but are not sufficient to determine a direct link to blunt trauma on the human thorax.

To address that issue, researchers, on the other hand, have used finite element (FE) modeling of the human torso to assess the risk of blunt injuries. Indeed, the development of computer methods over the past decades has first driven automotive industry to contribute to several complete FE model of the human torso, as for instance the Total Human Model for Safety (THUMS) and the Global Human Body Models Consortium (GHBMCM) [21–23]. Nonetheless, automotive impact conditions involve low speed and high mass, which oppose ballistic impacts with low mass and high speed. Therefore, many scientists have performed numerical simulations of human torso under non-penetrating ballistic impacts [14,24,25]. More precisely, the developed Hermaphrodite Universal Biomechanical YX model (HUBYX model) by Roth et al.

[25] and enhanced by Bodo et al. [26] is validated against ballistic impact replications and corresponding biomechanical corridors determined by Bir et al. [7]. Thus, this biofidelic torso model represents a reliable FE tools for the present study. However, it requires the knowledge of the exact geometrical and mechanical properties of the projectile, as well as, the impact conditions.

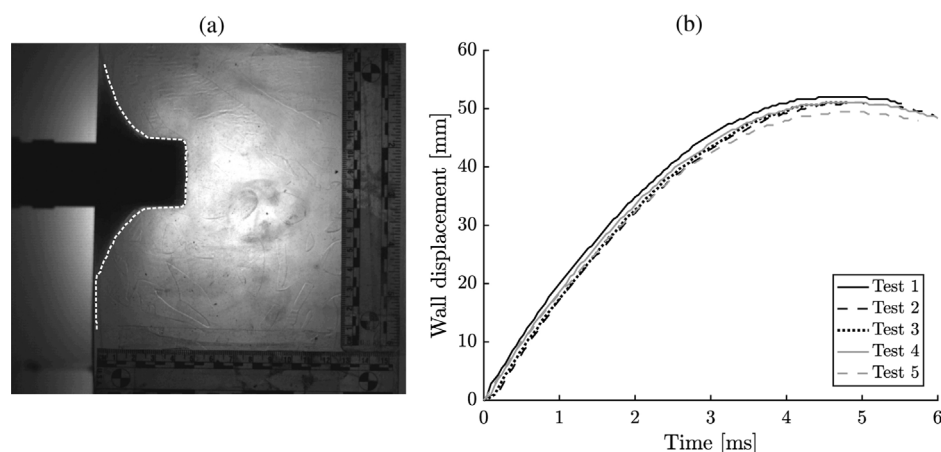
For these reasons, the present study aims to determine the wounding potential of any rigid LLKE projectiles by combining experimental and numerical data. In other words, the goal is to identify a suitable transfer function solely between experimental measurements on the synthetic gel and the probability of rib fractures. To the authors' knowledge, such a strategy is only briefly mentioned by Bracq et al. [27] without related outcomes on ballistic impacts. To that end, blunt ballistic experiments on the gel block are firstly depicted. Then, the human torso FE model HUBYX is succinctly described. Moreover, the statistical strategy developed in this study is presented. Finally, the results of this extensive study are shown and discussed.

## 2. Material and methods

### 2.1. SEBS gel and standard ballistic experiments

During ballistic experiments, the polymer gel SEBS is used as target medium to analyze and interpret experiments. The material involved in this study is a tri-block copolymer provided by Kraton Polymers LLC (Kraton G1652). A SEBS gel sample is created by mixing SEBS powder and mineral oil with 30wt% of SEBS having a styrene/elastomer ratio about 30/70%. The white mineral oil PRIMOL 352 is supplied by ESSO S.A.L. A complete detail of the sample preparation is mentioned by Bracq et al. [15].

Kinetic energy projectiles are impacted on a 25 cm gel block cube. These dimensions are chosen to neglect the influence of edge effects on the gel wall displacement. Then, a pneumatic launcher and a velocity sensor located at the barrel nozzle exit are employed to fire any type of projectiles at a desired velocity. The gel transparency leads to the measurement of the dynamic gel wall displacement profile in 2D through the simultaneous use of a lighting system and a high-speed camera Photron SA5 at 30,000 frames/s. For instance, Fig. 1a presents a photograph of the gel wall displacement due to an impact of a rigid round projectile of 37 mm in diameter at an initial speed of 20 m/s. More precisely, the white dotted line in Fig. 1a defines the contour of the gel wall displaced. The suitability of the experimental tests is also established by carrying out repeat impact tests at a single velocity. The consistency of the tests is highlighted with Fig. 1b, where five



**Fig. 1.** A photograph of the gel wall displacement during the impact of a rigid projectile (a) and experimental gel wall displacement curves for repeat impact tests at an initial velocity of 20 m/s (b).

tests result in a similar gel wall displacement time history with a relative displacement error less than 3.5%.

To interpret and to make the best use of ballistic experiments, the gel wall displacement may not be a sufficient measurement. In fact, as the risk of thoracic blunt trauma is better related to the rate of deflection than the deflection itself, a pseudo viscous-criterion called energy transfer parameter (ETP), expressed in mm/ms or in m/s, may be deduced from the gel wall displacement [28]. This new parameter has a similar mathematical model than the viscous criterion. It is determined by multiplying the gel wall displacement  $x(t)$  in mm and its derivative  $dx(t)/dt$  in mm/ms, and dividing by a specific value for normalization expressed in mm (see Eq. (1)) [29]. This value is related to the mean thorax depth.

$$ETP(t) = \frac{1}{196.5} \left( x(t) \frac{dx(t)}{dt} \right) \quad (1)$$

The displacement curves presented in Fig. 1b result in the calculation of the mean ETP response over time (see Fig. 2a). In addition, similarly to the viscous criterion, the maximum value of the ETP time history may be used to interpret experiments. Furthermore, the volume displaced during impact may be computed by assuming symmetry conditions. As a matter of fact, the 2D displacement contour at each time step leads to the calculation of the volume over time, as well as, its corresponding volume rate. Their respective maximum values  $Vol_{max}$  and  $VGR_{max}$  may be used to analyze experiments. Fig. 2b depicts the mean temporal evolution of the volume and its growth rate. This part constitutes a precise overview of the typical measurements which may be performed during an experimental impact on a gel block.

## 2.2. Human torso finite element model HUByx

The human torso FE model HUByx and its biofidelity are presented based on the study of Roth et al. [25] and Bodo et al. [26]. First of all, a 3D reconstruction of the human torso geometry is carried out based on CT scans image processing. Indeed, it enables to define both the skeleton and organs geometry with an aim of developing a 50th percentile male FE model. Then, the STL surface model is imported in Hypermesh software (Altair HyperWorks ©) to identify and mesh every component. The human torso model is constituted of skin and muscle, a skeleton and internal organs. A consistent mesh is built to obtain the best balance between model accuracy and computational costs. Therefore, it leads to a FE model of 37,900 8-nodes hexahedral elements and 77,800 4-nodes shell elements.

Fig. 3 describes the anterior human torso model indicating mesh discretization and main parts of the thorax including the skin and muscle (in transparency), the skeleton with essentially the

sternum, the costal cartilage, ribs and internal organs as lungs and the heart. With an aim of rib fractures investigation, Table 1 mentioned the material properties of the bone. The cortical part of the bone is modeled with shell elements and the spongy part with brick elements. More specific details about the contact interaction between torso parts, as well as, their material properties, can be found in the study of Bodo et al. [26]. Furthermore, dynamic impacts on the human torso model are simulated with the explicit code Radioss (Altair HyperWorks ©).

Concerning the biofidelity of the human model under non-penetrating ballistic impacts, it is validated against biomechanical corridors determined by Bir et al. [7] based on blunt ballistic impacts on PMHS. The human mid-sternum located between the third and fourth rib is impacted by rigid round projectiles of 37 mm in diameter (see Fig. 3). Three impact conditions: A, B and C, with different projectile masses  $m$  and velocities  $V$  are chosen during experiments: A ( $m = 140$  g,  $V = 20$  m/s), B ( $m = 140$  g,  $V = 40$  m/s) and C ( $m = 30$  g,  $V = 60$  m/s). Measurements and autopsy result in the calculation of a  $VC_{max}$  value for each test. Then, an injury score based on the Abbreviated Injury Scale is determined for each test and leads to the establishment of a probability curve of AIS score equal to 2 or 3 for skeleton injury as a function of the viscous criterion  $VC_{max}$  [6].

Whereas, Roth et al. [25] and Bodo et al. [26] have pointed out the model ability to predict the force and displacement evolution of the sternum during these ballistic conditions, one may pursue the investigation by calculating the  $VC_{max}$  value given by the HUByx model. This value is obtained by estimating the mean thorax depth by 236 mm [31]. Fig. 4 depicts the sternum deflection time history caused by the impact modeling of the condition A mentioned previously.  $VC_{max}$  evolution can be directly deduced, as well as, its maximum value.

Therefore, the  $VC_{max}$  values of the three impact configurations may be plotted on the probability curve of injury determined by Bir and Vian [6] (see Fig. 5). In addition, the statistical model based on experimental tests is evaluated by Bir and Vian [6] with  $\chi^2$ ,  $p$  and correlation coefficient  $R$  values indicated in Fig. 5. Furthermore, considering both the discrepancy between cadaveric specimens and  $VC_{max}$  range measured for each test condition, the HUByx model appears to be an appropriate FE model to predict the viscous criterion value for rigid kinetic energy projectiles impacting the human mid-sternum.

## 2.3. Statistical method for rib fractures assessment

The wounding potential of LLKE projectiles needs to be clearly assessed through a reliable strategy and consistent results (see Fig. 6). On the one part, impact experiments on the SEBS gel aim to

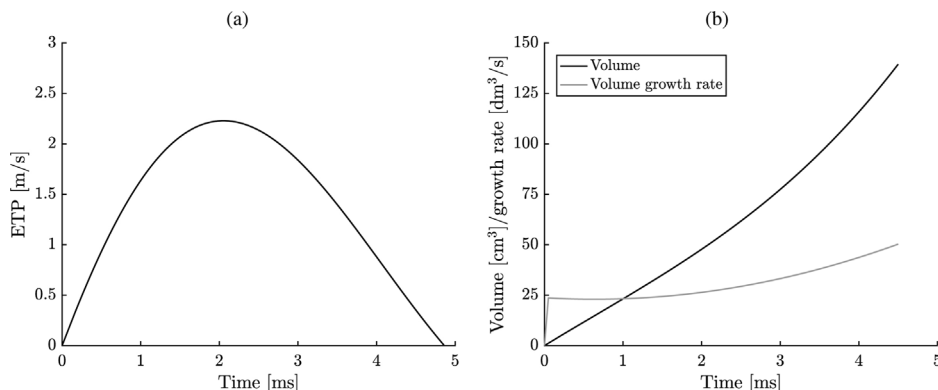


Fig. 2. Average experimental curves based on repeat impact tests at an initial velocity of 20 m/s: the energy transfer parameter as a function of time (a) and both the volume and volume growth rate as a function of time (b).

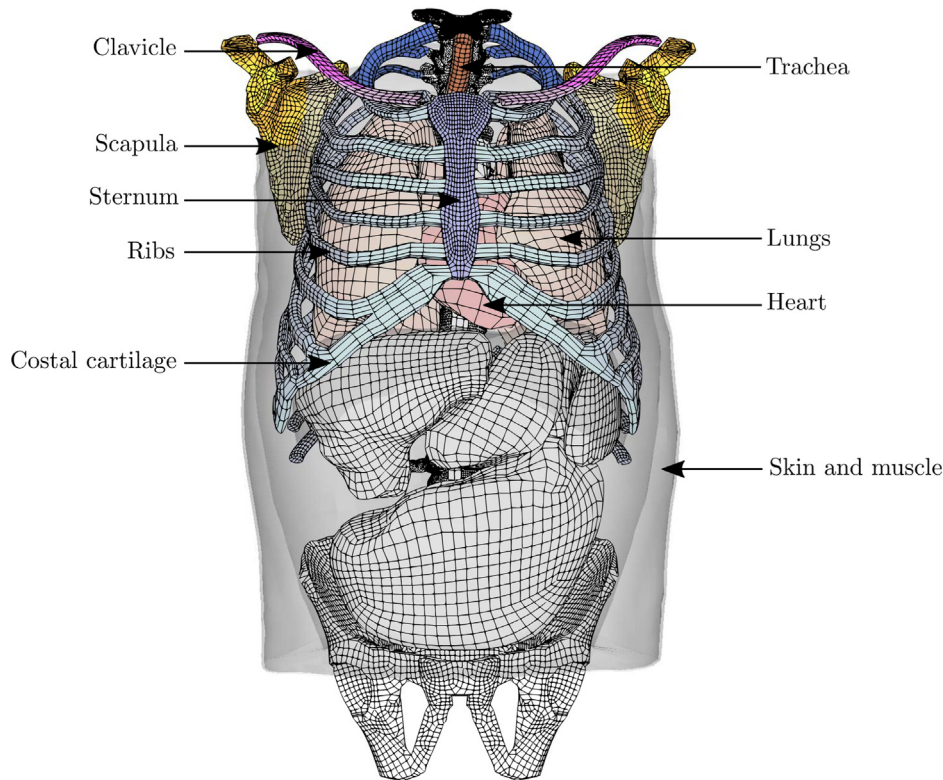


Fig. 3. Description of the human torso FE model HUByx.

**Table 1**  
Material characteristics of bony parts.

Bony parts	Material model	Young's modulus [MPa]	Poisson's ratio [-]	Yield stress [MPa]	References
Spongy	Elastic	50	0.4		Shigeta et al. [22]
Cortical	Elastic-plastic	14,000	0.3	70	Shigeta et al. [22] Yamada and Evans [30]

be used as a direct predicting tool towards blunt injuries. On the other part, this direct link with blunt trauma is established by the viscous criterion through both the HUByx model and cadaver experiments by Bir and Viano [6]. Therefore, the existence and reliability of a correlation between experimental measurements

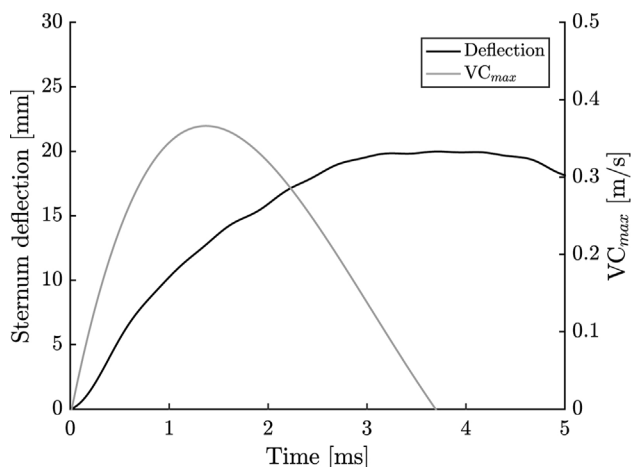


Fig. 4. Plot of sternum deflection over time and corresponding  $VC_{max}$  curve obtained from an impact modeling (Bir A condition, Bir et al. [7]) on HUByx.

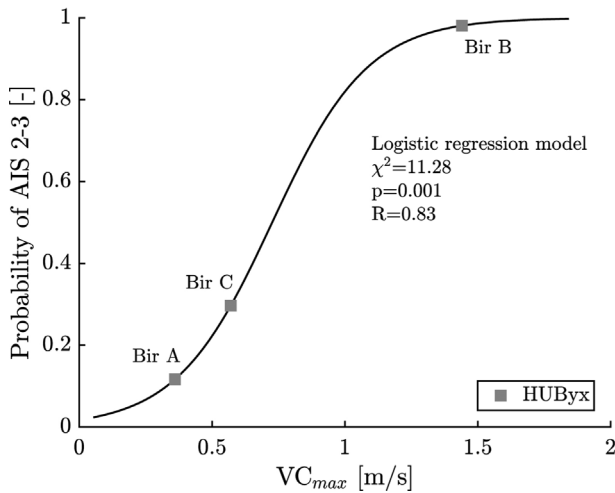
on the gel block and  $VC_{max}$  numerical values have to be carefully examined. To that end, an adequate amount of data is needed for correlation analysis. Indeed, 12 impact conditions with 4 different rigid projectiles are tested on the gel block and replicated on the human torso mid-sternum model. Table 2 resumes the impact conditions of 12 tests along with the FE modeling of the projectiles. Special cares have been taken in the mesh discretization of projectiles to avoid any discontinuity between the projectile and skin interface.

The first two projectiles remind the projectiles used in the studies of [6] and [7], as well as, the corresponding impact conditions designated by "Bir A", "Bir B" and "Bir C". Then, impact conditions are added with various impact velocities to obtain a wide range of kinetic energy from 10 to 252 J. Furthermore, the two hemispherical projectiles named "Hem30" and "Hem60" complete this range and the projectile momentum range.

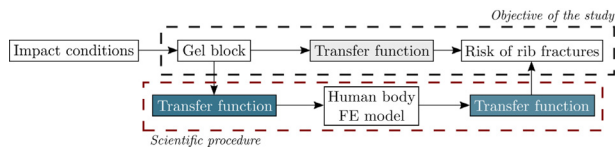
Thus, each test leads to a  $VC_{max}$  and a significant number of experimental data: the projectile mass, its initial velocity, momentum, kinetic energy along with the parameters mentioned previously: maximum ETP, displacement ( $x_{max}$ ), volume ( $Vol_{max}$ ) and volume growth rate ( $VGR_{max}$ ) values. As a consequence, a statistical analysis based on the establishment of a correlation matrix appears to be the most appropriate means to determine suitable correlations.

The statistical analysis is performed with MATLAB correlation functions (MathWorks ©). The significance and the degree of





**Fig. 5.** Probability curve of injury (AIS=2-3) as a function of the viscous criterion determined by logistic regression analysis from experimental cadaver tests and numerical values of  $VC_{max}$  calculated with HUByx [6].



**Fig. 6.** Chart describing the objective of the study as well as the scientific procedure combining experimental and numerical approaches.

correlation between experimental parameters and the viscous criterion are evaluated by virtue of respectively the  $p$ -value and the correlation coefficient. More precisely, the alpha risk is fixed at 0.05 for hypothesis tests. Indeed, the null hypothesis corresponds

to the absence of a relationship between the two studied variables. Moreover, the non-parametric Spearman's correlation coefficient is chosen to determine a correlation matrix between studied variables. Even though Pearson's correlation coefficient is essentially employed in correlation analysis, it only measures the linear relationship between two variables. Therefore, the extended ability of the Spearman's coefficient  $\rho$  to describe non-linear monotonic relationships makes it useful for the study.

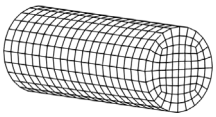
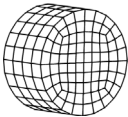
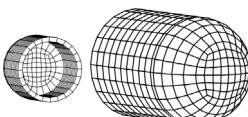
### 3. Results and discussion

#### 3.1. Correlation analysis

Table 3 refers to the Spearman's correlation matrix along with the determination of the  $p$ -value associated with each coefficient  $\rho$  based on 12 data pairs. Despite the alpha risk is set to 0.05 indicated with "\*", more restrictive alpha risk fixed at 0.01 and 0.001 are illustrated respectively with "\*\*" and "\*\*". Firstly, it is important to highlight relations governing experimental measurements on the gel block by means of the matrix analysis. In fact, it points out excellent correlations between the kinetic energy and the maximum gel wall displacement, the maximum volume, as well as, the ETP parameter with  $p$ -values  $<0.001$  and  $\rho$  coefficients  $>0.95$ . It is consistent with the fact that the projectile kinetic energy is entirely dissipated by the gel wall deformation due to its high stiffness and thus, dictates the gel response. Moreover, it may be assumed that for deformable LLKE projectiles, a significant part of the projectile kinetic energy would be dissipated by its deformation and the other part by its target. Therefore, the kinetic energy parameter is not expected to be such a relevant parameter to correlate with the viscous criterion. Consequently, the analysis moves toward the correlations between experimental parameters and the viscous criterion.

The maximum volume and its maximum growth rate constitute relevant parameters for their correlation with the viscous criterion

**Table 2**  
Description of projectiles and impact conditions throughout the study.

Description	Denomination	Diameter [mm]	Mass [g]	Velocity [m/s]	Kinetic energy [J]
	Bir A	37	140	12	10
	Bir B			20	28
				30	63
				40	112
				50	175
	60	252			
	Bir C	37	30	60	54
	Hem30	40	30	52	40
80				96	
	Hem60	40	60	18	10
				22	15
				45	61

**Table 3**

Spearman's correlation matrix with the determination of the statistical significance.

Data source	Variables	1.	2.	3.	4.	5.	6.	7.	8.
Projectile	1. Mass [g]								
	2. Velocity [m/s]	-0.462							
	3. Kin. energy [J]	0.262	0.701*						
	4. Mom. [kg m/s]	0.637*	0.354	0.874***					
Experiment	5. $x_{max}$ [mm]	0.194	0.718**	0.984***	0.834***				
	6. $Vol_{max}$ [cm <sup>3</sup> ]	0.467	0.494	0.923***	0.937***	0.886***			
	7. $VGR_{max}$ [m <sup>3</sup> /s]	-0.102	0.883***	0.846***	0.615*	0.837***	0.762**		
	8. ETP [m/s]	0.068	0.764**	0.951***	0.720**	0.970***	0.846***	0.771**	
HUByx	9. $VC_{max}$ [m/s]	0.193	0.721**	0.986***	0.839***	0.998***	0.839***	0.862***	0.972***

Note: \* $p < 0.05$ , \*\* $p < 0.01$ , \*\*\* $p < 0.001$ , Number of observations = 12

due to  $\rho$  coefficients  $>0.86$  and  $p$ -values  $<0.001$ . However, the maximum gel wall displacement and the energy transfer parameter point out even greater correlations with the viscous criterion considering  $\rho$  coefficients  $>0.97$  and  $p$ -values  $<0.001$ . As a result, it leads to the determination of monotonic transfer functions between the two latter experimental parameters and the viscous criterion. A 2nd degree polynomial model is proved to be a highly suitable mathematical formulation to describe the two relations (see Fig. 7a and b). More precisely, these two figures present the 12 data pairs for the two relations mentioned previously along with their polynomial fit using the MATLAB Curve Fitting Toolbox (MathWorks ©). Moreover, confidence intervals for fitted functions are plotted in dotted line corresponding to a 95% level of certainty. In addition, Fig. 7a and b indicates the polynomial equations with their associated coefficients. Special cares are taken to reach a null value for the transfer function at its origin in order to obtain consistent relations. Furthermore, infinitesimal  $p$ -values and  $R$ -squared determination coefficients  $>0.95$  for the related transfer functions complement their ability to accurately describe the relations between experimental parameters and the viscous criterion.

### 3.2. Identification of transfer functions

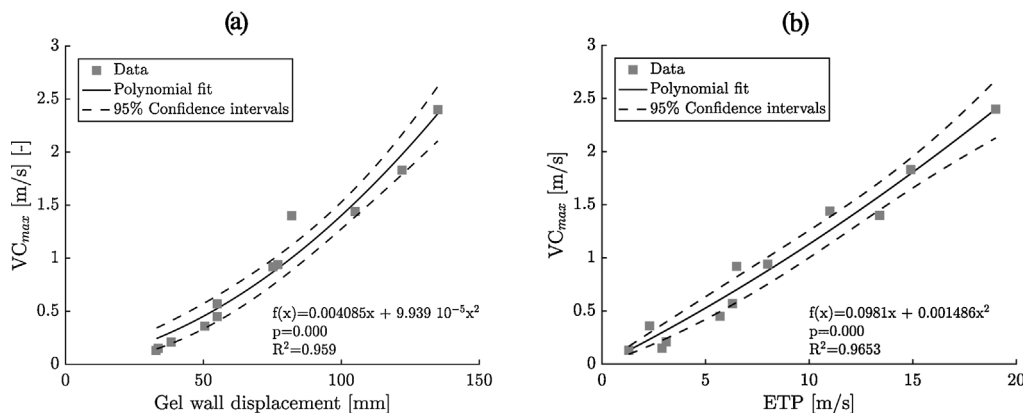
In view of the statistical analysis and its outcomes presented, the identified transfer functions may be employed to directly relate with the probability of rib fractures described in Fig. 5. Indeed, the risk of injury curve versus the viscous criterion results in two probability curves of an AIS score equal 2 or 3 for rib fractures as a function of the experimental gel wall displacement parameter and the energy transfer parameter ETP. Fig. 8a describes the first important relation of this study between the risk of injury and

solely an experimental measurement. In the same way, Fig. 8b represents the second crucial relation with the risk of injury response related to the energy transfer parameter. Moreover, Fig. 8a and b indicates the logistic regression functions and 50% risk of injury values for both the gel wall displacement parameter and the energy transfer parameter.

These two relations enable to determine the wounding potential of rigid LLKE projectiles exclusively based on a gel block test and associated measurements. Thus, they may be employed to design new projectiles to limit the risk of rib fractures and plausible underlying injuries. Then, the established transfer functions are related to the study of Bir and Viano [6] and for that reason, are uniquely valid for a mid-sternum impact. Moreover, the maximum gel wall displacement parameter is related to the projectile kinetic energy for the case of stiff projectiles. Consequently, a rigid projectile and a deformable projectile may result in an equivalent viscous criterion value with distinct gel wall displacement metrics. Hence, it may be assumed that the energy transfer parameter, taking into account the rate of gel wall displacement, constitutes the only relevant experimental parameter to assess the wounding potential of various types of LLKE projectiles.

### 4. Conclusion

The risk of rib fractures caused by rigid LLKE projectiles is assessed through experimental and numerical approaches based on literature investigations on PMHS [6,7]. The requirement of experimental tests leads to the use of a polymer SEBS gel block as a transparent target medium in order to measure and interpret dynamic deformation caused by blunt impacts. It results to be a robust and consistent tool to measure different pairs of parameters



**Fig. 7.** Plots of injury criterion  $VC_{max}$  data, respective polynomial fitting function and confidence intervals as a function of the gel wall displacement (a) and the energy transfer parameter (b).

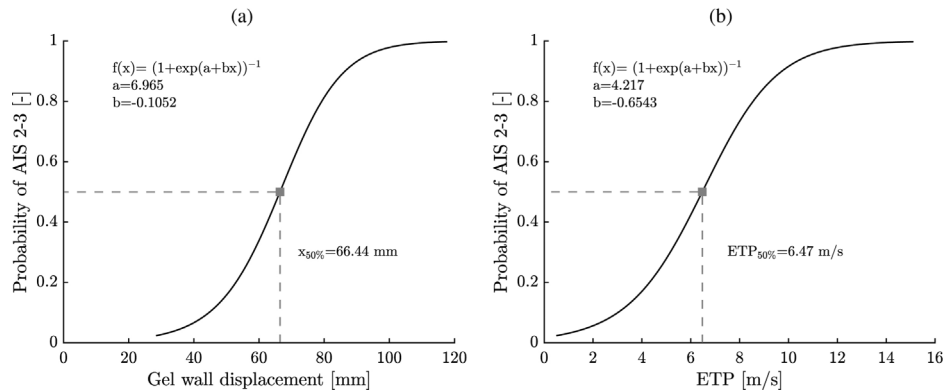


Fig. 8. Probability curves of injury (AIS=2-3) as a function of the gel wall displacement (a) and the energy transfer parameter (b).

as for instance, the maximum gel wall displacement, the ETP value. Then, a biofidelic human torso FE model named HUByx is employed to replicate experimental tests and relate with the viscous injury criterion.

A strategy is proposed based on a statistical analysis to establish reliable transfer functions between solely experimental data on the gel block and the probability of rib fractures based on 12 data pairs. More precisely, a Spearman's correlation matrix is determined to get insight into relations governing experimental data, as well as, the existing correlations between experimental data set and the viscous criterion. It leads to the determination of robust 2nd degree polynomial transfer functions with  $R$ -squared values  $>0.95$ . These functions imply suitable relations between the gel wall displacement parameter and the energy transfer parameter with the probability of rib fractures. These correlations constitute a key predicting tool for the assessment of a projectile wounding potential for impacts occurring on the human mid-sternum. However, specific considerations and investigations remain to be completed to extend this procedure to deformable LLKE projectiles and other impact locations.

### Conflict of interest

The authors have no conflicting interests regarding this paper.

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