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On the use of a SEBS polymer gel block as a new ballistic target to assess blunt ballistic impacts: application to a wide range of LLKE projectiles.

A. Bracq[a,1,*], R. Delille[a], C. Maréchal[a], B. Bourel[a], F. Lauro[a], S. Roth[b], O. Mauzac[c]

[a] *Laboratory LAMIH UMR 8201 CNRS, University Polytechnique Hauts-de-France, 59313 Valenciennes, France*
[b] *Interdisciplinary Laboratory Carnot of Bourgogne, UTBM, UMR CNRS 6303, University of Bourgogne Franche-Comté (UBFC), 90010 Belfort, France*
[c] *French Ministry of the Interior, CREL/SAELSI, Place Beauvau, Paris, France*

Abstract

The objective of the present paper is to determine the ability of a transparent polymeric gel, used as a reference material with a mechanical response comparable to that of a human body, to assess less-lethal kinetic energy (LLKE) projectiles. To do this, a consistent measurement method of the dynamic deformation of the gel impacted by a projectile is first of all presented. It relies on high-speed images and image processing routines. Several metrics from the measured gel wall displacement profile are used to investigate experiments. Secondly, repeated impact conditions on various gel blocks confirm that, the proposed material meets the requirements of mechanical consistency, batch-to-batch reproducibility and easy handling. Thirdly, 138 ballistic experiments covering kinetic energies from 10 J up to 300 J are performed, involving commercially available LLKE projectiles of various stiffness. The important dataset is used to perform a statistical analysis through Spearman's correlation matrix between metrics and projectile parameters. It mainly reveals the need to use a ballistic target to determine the wounding potential of a given projectile rather than kinetic energy density or momentum density. Robust power law mathematical fits describe the relations between three metrics (maximum gel displacement, displacement - rate of displacement-based metric and maximum displaced volume) and kinetic energy density depending on LLKE projectiles' stiffness. Fourthly, three case reports available in literature and involving LLKE projectiles have been replicated on a gel block. An experimental procedure is proposed based on numerous case reports to give design guidelines in terms of projectile mass, velocity and stiffness. Finally,

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this original study demonstrates the gel material capabilities to assess LLKE weapons before their field deployment. However, further investigations need to be pursued to propose a relevant injury predictive tool and associated risk curves to law enforcement agencies and regulatory bodies.

Keywords: Non-penetrating ballistic impact, Less-lethal projectile, Experimental testing, Image processing, Statistical analysis, Blunt trauma

1. Introduction

Over the past few centuries, ballistic impacts have been studied to improve ammunition efficiency and precision. Accordingly, innovative personal protective systems have been designed to protect the human body. For decades, biomechanical interactions have been studied to understand and mitigate ballistic trauma. Severe injuries may arise from non penetrating or blunt ballistic impacts. Behind Armour Blunt Trauma (BABT) is the term used to define trauma due to the dynamic deformation of the body armour. Since the 1970's, modern conflicts in Western civilisations have resulted in the use of Less-Lethal Kinetic Energy projectiles (LLKE) especially for riot control purposes. Tailor-made kinetic energy projectiles are also employed to simulate BABT on animals [1]. Such non penetrating ballistic impacts may also lead to serious physiological and physical injuries, as reported by many authors [2, 3, 4, 5, 6].

In view of these observations, authorities' concerns have led to clinical studies on Post-Mortem Human Subjects (PMHS) and anaesthetised animals. These aim to quantify the injury potential of LLKE projectiles by gaining a comprehensive understanding of ballistic blunt trauma [7, 8, 9]. One of the major outcomes of the clinical study of Bir and Viano [8] is the use of the viscous criterion (i.e. thoracic wall displacement rate dependent model) as an explanatory variable to predict the risk of rib and sternum fractures [8, 10]. Nevertheless, conclusions only rely on

*Corresponding author. Tel.: +33(3) 89 69 50 94
Email address: anthony.bracq@isl.eu (A. Bracq)
[1]Present address: French-German Research Institute of Saint-Louis, 68300 Saint-Louis, France

plastic baton rounds impacting PMHS' sternum at a maximum kinetic energy of 112 J. In spite of these encouraging results, cadaver and animal testing remains challenging and raises ethical issues. One of the main drawbacks is the difficulty of testing multiple projectiles over a wide range of kinetic energies.

To address this matter, homogeneous soft materials have been created to mimic human body tissue. 10 and 20 wt% ballistic gelatin are two standard materials mainly utilised to gain insight into penetrating and blunt impacts and effects on the human body [11, 12, 13, 14]. Hanlon and Gillich [15] also provide elements in favour of ballistic gelatins properties for use in describing the backface dynamics of body armour. Nonetheless, numerous studies have highlighted several practical issues using ballistic gelatins. This material exhibits prohibitive properties such as a precipitate ageing time, a poor thermal stability, a significant humidity sensitivity and a low transparency [16, 17, 18]. Therefore, synthetic tissue simulant materials have been recently developed. Ballistic gelatins from Clear Ballistics and styrene-ethylene-butylene-styrene (SEBS) polymer-based materials are examples of stable, reusable and transparent synthetic targets [19, 20, 21, 22, 23, 24]. Moreover, Mrozek et al. [25] have highlighted the versatility of SEBS polymer gel. Its mechanical properties can be tuned by adjusting polymer concentration.

Researchers have also proposed hybrid experimental-numerical methods to assess ballistic impacts and the wounding potential of projectiles [26, 27]. Dynamic impact tests of compliant LLKE projectiles on a rigid wall have been used to simulate ballistic impacts on human body finite element models (FEM) [27, 28, 29]. Nonetheless, such investigations are time consuming and intricate. Moreover, outcomes depend upon FEM and material laws describing body parts' behaviour. Experimental investigations are thus mandatory to evaluate projectiles and provide guidelines for their design at a latter stage. Tawell [30] has reported momentum and kinetic energy based threshold values above which "serious injury is highly likely to occur". Indicated values of 5000 $kg.s^{-1}.m^{-1}$ (impulse by unit area) and 200 J are not representative of previous case reports [8, 4]. An impulse of 2100 $kg.s^{-1}.m^{-1}$ and a kinetic energy of 112

J were sufficient to cause serious injuries to the human torso. Additionally, Kapeles and Bir [31] have outlined the limitations of a kinetic energy based injury criterion when dealing with compliant LLKE projectiles. To the authors' knowledge, no research provides sufficient data and a reliable experimental procedure to assess LLKE projectiles before their field deployment.

Consequently, the objective of the present paper is to propose a consistent experimental target to both evaluate blunt impacts and introduce novel mass-velocity guidelines for LLKE projectiles. As illustrated by Fig. 1, the scientific procedure consists in using transparent SEBS polymer gel blocks as ballistic targets. Multiple impact shots using various LLKE projectiles will constitute a database of experimental measurements which are mandatory to perform a statistical and biomechanical analysis. In the first instance, materials and methods involved in this study are described, from ballistic experiments to statistical analyses. In a second phase, the robustness of the proposed ballistic target is shown based upon repeated experiments on several manufactured gel blocks. Then, a substantial number of test results are used to identify relevant experimental metrics to analyse an impact. Finally, impact conditions detailed in case reports are replicated on gel blocks. This highlights the potential of gathering case studies when giving design guidelines according to the projectile's stiffness.

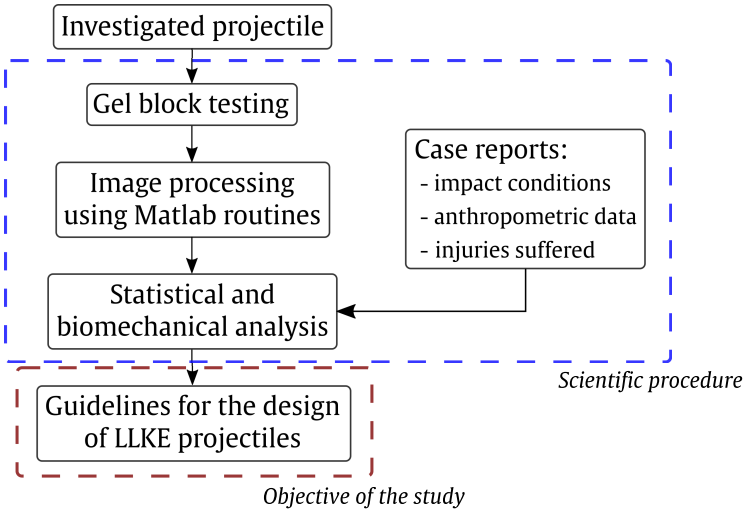


Figure 1: Flow chart representing the scientific procedure and the objective of the study involving ballistic experiments, statistical and biomechanical analysis.

2. Materials and methods

2.1. Projectiles involved in the study

In order to assess the influence of LLKE projectiles and related mechanical properties as well as shooting parameters on a ballistic target, four homogeneous LLKE projectiles and four hybrid LLKE projectiles are used during experiments (see Tables 1 and 2). Homogeneous projectiles of 37 mm in diameter (PBR and S-PBR) are made of plastic. Hemispherical projectiles (HEM) of 40 mm in diameter are designed by the French Ministry of the Interior based on high-density polyethylene material. Foam is also used to manufacture Flash-Ball® projectiles. Then, hybrid projectiles of 40 mm in diameter are made of a compliant nose and a rigid rear part. Rubber and foam materials of different densities are used to tune the mechanical properties of projectiles. The shooting parameters of these commercially available projectiles are chosen to cover a wide range of kinetic energies (from 10 J up to 300 J). More precisely, Tables 1 and 2 indicate the geometry, the mean mass and the kinetic energy distribution of each projectile. 138 impact experiments are thus performed to obtain reliable statistical analyses. Among these projectiles are two

solid rubber projectiles (PBR and S-PBR) used in the clinical study of Bir and Viano [8] and Bir et al. [7] and two soft projectiles (Flash-Ball® and eXact iMpact™) used in two real world incidents depicted by Wahl et al. [5] and Kobayashi and Mellen [4] respectively.

Table 1: Description of homogeneous less-lethal kinetic energy projectiles and impact conditions applied to the ballistic target.

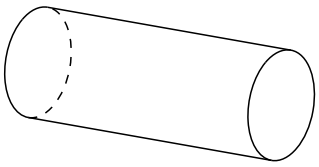
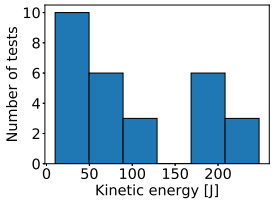
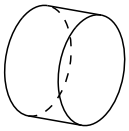
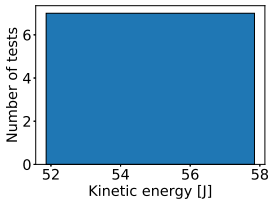
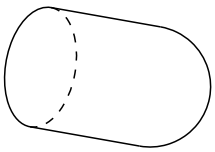
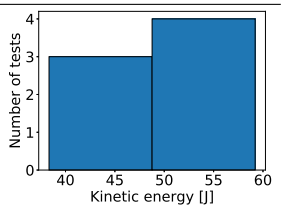
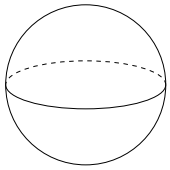
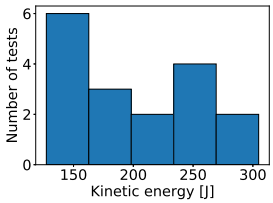
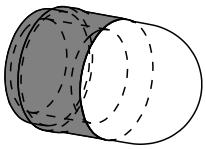
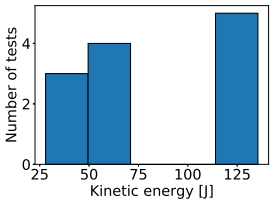
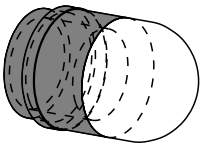
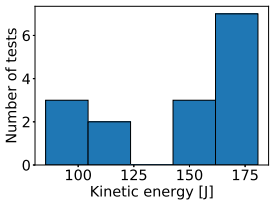
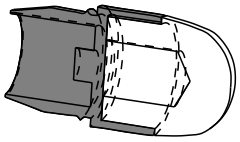
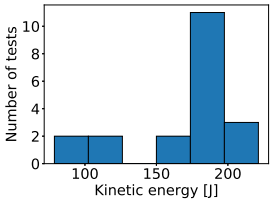
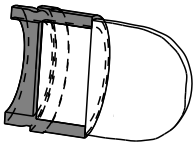
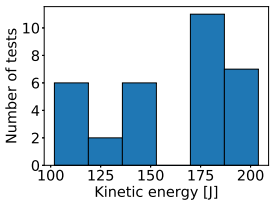
Projectile	Name (Manufacturer)	Diameter $[mm]$	Length $[mm]$	Mass $[g]$	Kinetic energy distribution
	PBR Pains-Wessex Schermuly	37	100	140	
	S-PBR SIMAD S.p.A	37	22	30	
	HEM French Ministry of the Interior	40	65	59	
	Flash-Ball (Verney-Carron)	44	44	28	

Table 2: Description of hybrid less-lethal kinetic energy projectiles and impact conditions applied to the ballistic target.

Projectile	Name (Manufacturer)	Diameter [mm]	Length [mm]	Mass [g]	Kinetic energy distribution
	eXact iMpact (Defense Technology)	40	62	29	
	B&T (Brgger & Thomet)	40	62	32	
	ALX2015 (Alsetex)	40	78	62	
	CTS4557 (Combined Tactical Systems)	40	62	60	

2.2. *Polymer gel block and ballistic experiments*

All ballistic experiments described in this study are carried out using polymeric gel SEBS blocks as ballistic targets. In order to constitute a SEBS gel block, SEBS copolymer powder provided by Kraton Polymers LLC (Kraton G1652, a linear styrene-ethylene/butylene copolymer with a styrene/rubber ratio of 30/70%) is mixed with mineral oil PRIMOL 352 produced by ESSO S.A.L. A SEBS powder/mineral oil ratio of 30/70% is chosen. More information about the material processing of SEBS gel samples can be found in the research studies of Bracq et al. [23, 32].

A 25 cm gel block cube is used during ballistic impacts in order to minimise the influence of edge effects on the gel wall displacement in both vertical and horizontal directions. Figure 2 describes the experimental set-up used

for the analysis of ballistic impacts. A pneumatic launcher is used together with a 100 mm light gate with an exit beam at 15 cm from the target to measure the impact velocity. The gel block and the barrel are placed in such a way to strike the centre of the gel block. As the barrel nozzle exit is located 15 cm from the gel block surface, the obliquity is equal or very close to 0, which is checked using the high-speed video record. Gel transparency along with a backlighting device and a high-speed camera capture the ballistic event and, specifically, the gel wall displacement profile over time. Images are recorded at 20,000 up to 46,000 frames per second. Image resolution and camera positioning give a calibration factor ranging from 0.35 to 0.45 mm/pixel. Light rulers are fixed to the gel surface, leading to the conversion into physical dimensions of the 2D gel wall displacement profile. Special care is taken to adjust the measurements by applying Thales' theorem (geometrical corrections) and Snell's law (effect of the refractive index of the gel). The corrected gel wall displacement at the centre of the block is obtained by using the gel block thickness and the distance between the camera lens and the gel block surface as well as a gel refractive index n=1.44. Specific routines coded through a graphical user interface (GUI) within the MATLAB environment (MathWorks ©) are developed to compute the 2D gel wall displacement profile for each frame using gray level thresholding. This technique is validated against the gel wall displacement measured by a quasi-static press equipped with a hemispheric plunger. An average error of 0.6 mm is computed between the machine traverse and the image processing routine for a wide range of target displacements. The next part of this paper gives a complete overview of the experimental metrics resulting from a ballistic impact analysis.

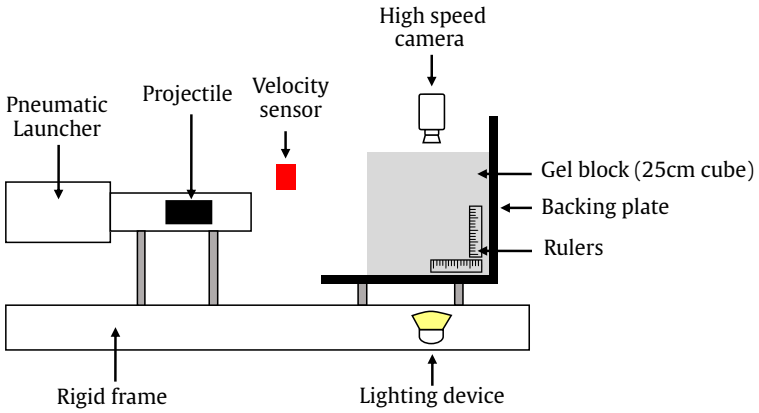


Figure 2: Schematic of the experimental set-up used for the analysis of ballistic impacts [24].

Fig. 3a is a photograph of the maximum gel wall displacement during an impact of a rigid hemispherical projectile (HEM) at an initial speed of 43 m/s. The red line displayed in Fig. 3a coincides with the contour of the displaced gel wall identified by the image processing routine. On the left side of Fig. 3a, the velocity sensor placed at the barrel nozzle exit may be observed. Capturing the contour for each time frame leads to the main measurements presented in Fig. 3b. It corresponds to the 2D gel wall displacement profile over time. Based on this key result, various measurements can be deduced. The maximum gel wall displaced time history is obtained, but with specific considerations (see Fig. 4a). In fact, as the early stages of the gel wall displacement (less than 5 up to 10 mm) cannot be detected by the camera due to optical issues, the time of impact is unknown. To overcome this problem, the solution describing an underdamped harmonic oscillator (UHO) system is used to fit the gel wall displacement during the main rising time and predict the time of impact. The choice of this mathematical model defined in Eq. 1 is validated by evaluating the R-squared coefficient of determination. In this example, its value is 1.000 supporting the choice of the model.

$$f(x) = ae^{-bx}sin(cx + d) \tag{1}$$

where a, b, c and d are parameters to identify using curve fitting algorithms. It estimates the temporal shift to apply in order to obtain a null displacement at time zero.

Literature has also highlighted the fact that the risk of trauma correlates better with the rate of body wall deflection rather than with the deflection itself [10]. Therefore, a pseudo viscous-criterion known as energy transfer parameter (ETP), expressed in m/s, is deduced from the gel wall displacement data and corresponding UHO fit (see blue markers and red line in Fig. 4a) [33]. The mathematical equation of this new metric is analogous to the viscous criterion and is defined by Eq. 2 [34]. More precisely, the ETP time history applied to this impact is related to both the gel wall displacement and the rate of displacement. Fig. 4b shows the time evolution of this metric.

$$ETP(t) = \frac{1.3}{255.5}\left(x(t)\frac{dx(t)}{dt}\right) \tag{2}$$

where 1.3 is used as a pre-factor and 255.5 is related to the mean thorax depth in mm [34]. Moreover, assuming axisymmetric cross-sections, the 2D gel wall displaced profile displayed in Fig. 3b may be exploited to compute the displaced volume, expressed in cm^3 for each time step and its derivative, the volume growth rate (VGR), expressed in dm^3/s. The volume is estimated according to Eq. 3 where n is the number of tracked points or the number of rows in the image. S_i is the projected area for each point i and x_i its depth. Equations 4 and 5 define the variables y_i^* and dy_i respectively, used to compute S_i. Eq. 3 is graphically represented in Fig. 5. Fig 4c depicts the displaced volume and a modified UHO fit (see Eq. 6) with the R-squared value. This equation takes complex non linearity into account while maintaining the limit conditions: at time zero, the volume displaced should be zero. Fig 4d shows the computed volume growth rate using raw data and fitted model as a function of time. The maximum values of the aforementioned measurements represent ballistic metrics and may be used to compare and assess ballistic impacts. They are defined

by X_{max}, ETP_{max}, VOL_{max} and VGR_{max}, related to the gel wall displacement, the ETP, the displaced volume and the volume growth rate respectively. ETP_{max} and VGR_{max} values relate to fitted curves minimising data scattering. The time period to reach the maximal gel wall displacement, $t_{X_{max}}$, expressed in ms, can serve as an additional metric to analyse ballistic experiments.

$$\begin{aligned} V &= \sum_{i=0}^{n} S_i x_i \\ S_i &= \pi dy_i \left(y_i^* - \frac{dy_i}{2} \right) \end{aligned} \tag{3}$$

where,

$$y_i^* = |y_i - y_{\max\limits_{i=1,\dots,n}\{x_n\}}| \tag{4}$$

and,

$$dy_i = |y_i - y_{i+1}| \tag{5}$$

$$f(x) = ae^{-bx} tanh(cx)^d \tag{6}$$

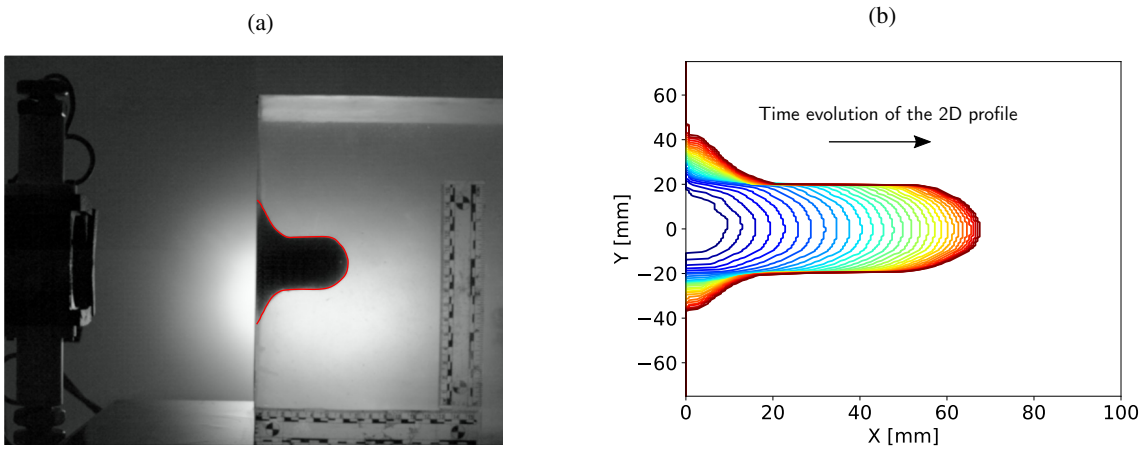


Figure 3: A photograph of the gel wall displacement taken by a high-speed camera during the impact of a rigid projectile at an initial velocity of 43 m/s (a) and corresponding 2D gel wall displacement profile curves as a function of time (b).

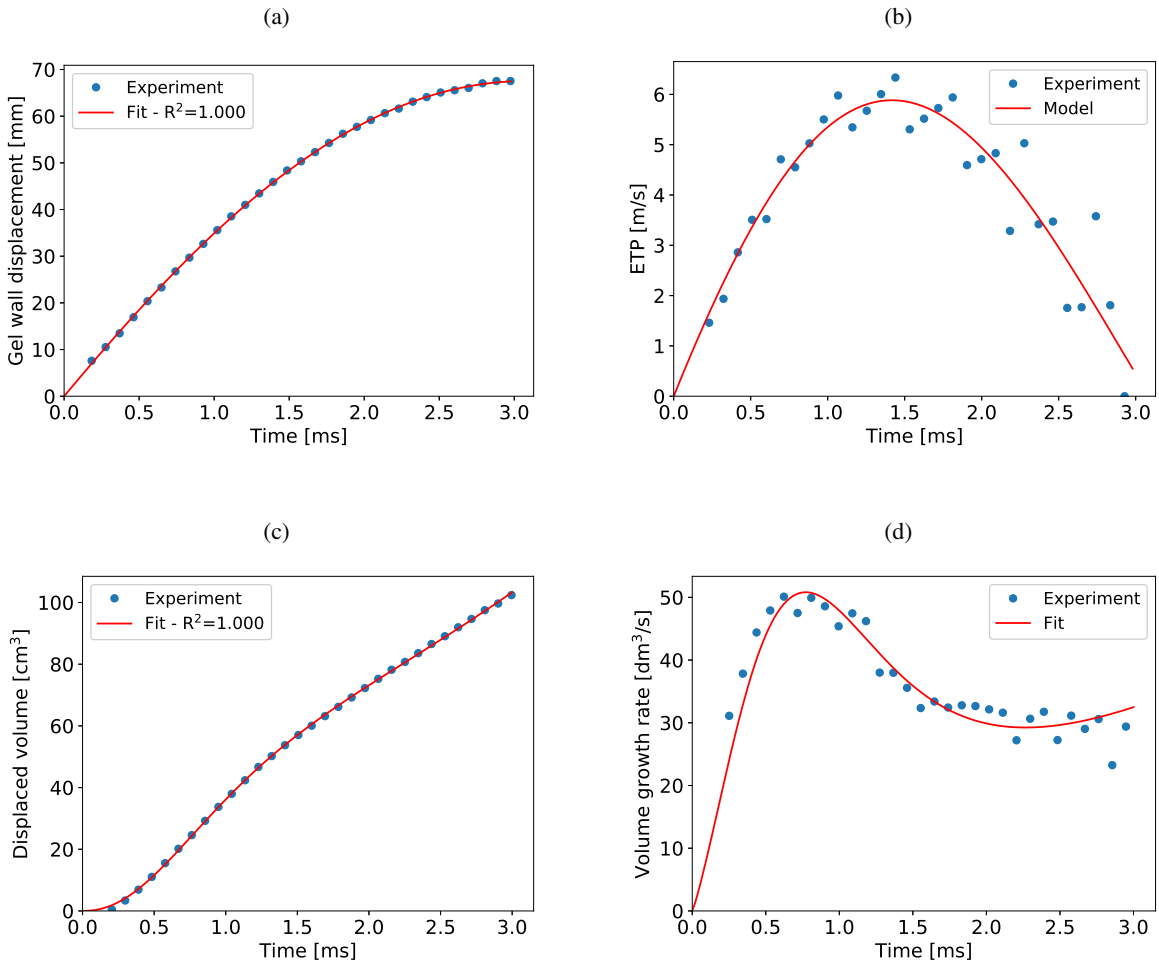


Figure 4: Experimental curves computed from the 2D gel wall displacement profile time history: the maximum gel wall displacement (a), the energy transfer parameter (b), the displaced volume and the volume growth rate (d) over time.

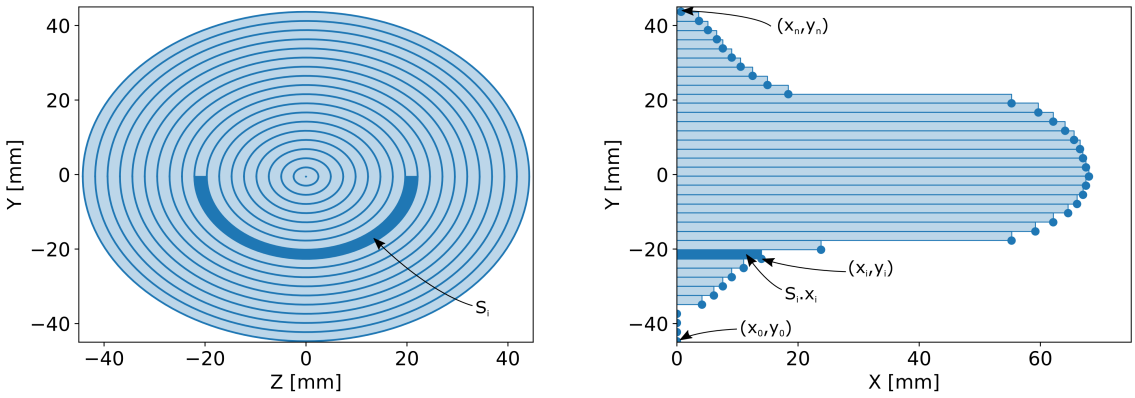


Figure 5: Graphical representation of how displaced volume is computed (note: only one point out of four is displayed for easier visualisation).

2.3. *Statistical analysis*

The statistical analyses performed in this paper serve two purposes. The first one is to assess the proposed ballistic target. The gel block has to fulfil various essential requisites in order to be adopted by law enforcement agencies, research laboratories, regulatory bodies and weapon manufacturers. Besides being easy to handle, the ballistic target has to demonstrate a mechanical consistency and ensure a batch-to-batch reproducibility. In other words, it means that repeated impact tests on a unique gel block have to present consistent results and carrying out comparable experiments on various blocks should not affect the results. To address this matter, equivalent impact conditions described in Table 3 and involving hemispherical rigid projectiles (HEM) have been applied to four SEBS gel blocks produced using the same preparation method. In addition, mean and standard deviation (written in parentheses) values of the projectile mass, velocity, kinetic energy and momentum are indicated for each gel block based on a specific number of tests (see Table 3). Among these four blocks, three were produced in 2018 and one in 2014. The influence of ageing on the gel mechanical response is determined by performing impact tests, shown in Table 3, in November 2018. A one-way ANOVA analysis is performed where each block is compared to one another. The null hypothesis H_0 states that there is no difference in means of tested gel blocks.

Table 3: Description of the projectile and impact conditions applied to the ballistic target to assess its mechanical consistency and its batch-to-batch reproducibility.

Projectile	Gel block	Number of tests	Mass [g]	Velocity [m/s]	Kinetic energy [J]	Momentum [kg.m/s]
HEM	B1-2014	4	58.93 (0.10)	43.70 (0.88)	56.28 (2.28)	2.58 (0.05)
	B2-2018	5	59.26 (0.09)	43.86 (1.38)	57.04 (3.56)	2.60 (0.08)
	B3-2018	4	59.10 (0.11)	43.63 (1.50)	56.29 (3.96)	2.58 (0.09)
	B4-2018	7	58.36 (0.18)	45.34 (1.38)	60.04 (3.72)	2.65 (0.08)

The second purpose is to identify and quantify the potential correlations between the experimental metrics related to the gel and the physical metrics linked to the impact conditions, as for instance the impact velocity or the kinetic energy. 138 impact conditions, described in Tables 1 and 2, have been applied to four gel blocks covering a wide range of kinetic energies and projectile types. Experiments are randomly performed on each block and the gel block surface is inspected after each test. A 5 mm crack is the threshold length above which another gel block side is used as the target surface. In the case of extreme degradation , the block is simply re-melted. Spearman's correlation matrix is established based on these 138 data sets using MATLAB correlation functions (MathWorks ©). The significance and the degree of correlation are evaluated between each metric by virtue of the p-value and Spearman's correlation coefficient ρ respectively. In this study, the alpha risk is fixed at 0.05 for hypothesis tests. The null hypothesis is defined by the absence of a linear or non-linear monotonic relationship between the two metrics studied.

The following part of this article aims to present and discuss the extensive results of this research underlining the main benefits of this ballistic target to assess non-penetrating impacts and, above all, less-lethal kinetic energy projectiles.

3. Results and discussion

3.1. Assessment of the proposed ballistic target

The first main result of this study relies on the assessment of the mechanical consistency and reproducibility of the proposed polymer-based material as ballistic targets. According to Table 3, at least four equivalent shots have been performed on each manufactured gel block. To discuss the reliability of the image processing method and the ballistic target, box plots have been drawn based on maximum gel wall displacement and displaced volume data according to the gel block number (see Fig. 6). It quantifies the scattering of experiments inter- and intra-gel blocks. Each individual block reveals a low dispersion, regarding the maximal gel wall displacement metric, with a maximal span around the mean of +/- 3 mm. Average data is plotted using blue crosses. Fig. 6a also highlights the very good batch-to-batch consistency due to the fact that for four different gel blocks, the average maximal gel wall displacement is between 70.5 and 71.2 mm. Using gel wall displacement data from 20 tests for a one-way ANOVA analysis, the null hypothesis cannot be rejected. It means there is statistically no significant difference between the blocks with a *F-statistical value* of 0.63 and a *p-value* equal to 0.89. Consequently, considering the time frame 2014-2018 and the use of four gel blocks, ageing appears to have no significant effect on the gel block response when subjected to direct impacts. Fig. 6b shows a more important discrepancy in the maximum displaced volume inter- and intra-gel blocks. This mainly arises from variations, which may occur between experiments in horizontal and vertical directions, and are magnified by computing the displaced volume. Hence, the maximum displaced volume metric outlines a reasonable scattering between gel blocks with a mean volume ranging between 120 and 128 cm^3. As the ballistic target and proposed image processing methodology demonstrate an important robustness, the analysis of 138 impact conditions applied to gel blocks is possible. It aims to demonstrate the requirement of using a convenient ballistic target when investigating different types of LLKE projectiles.

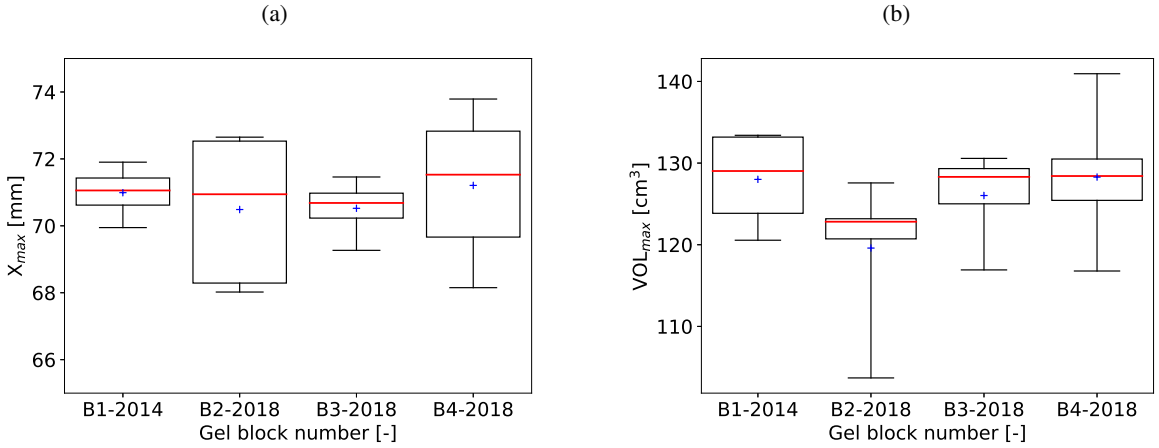


Figure 6: Scatter plots of the maximum gel wall displacement (a) and the maximum displaced volume (b) as a function of the gel block number used during impact experiments.

3.2. Identification of relevant experimental metrics

The second main objective of this study is to determine the effect of impact conditions, i.e. projectile nature, mass, velocity, kinetic energy density (KED) and momentum density (MD), on the target material response. The gel block is supposed to capture how a given projectile may interact with the human body. To deal with this matter, 138 ballistic tests (see Table 1) covering 30 distinct impact conditions are applied to gel blocks. The high number of tests ensure repeatability and give confidence in statistical analyses. As impacting the ballistic target at a desired velocity is well mastered by the experimental set-up described in Fig. 2, the scattering around the mean velocity is low for the entire dataset. Experimental metrics measured using the image processing routine present a minor dispersion, especially as regards the maximal gel wall displacement (X_{max}), rising time ($t_{X_{max}}$) and energy transfer parameter (ETP_{max}). As mentioned previously, the maximum displaced volume has a higher scattering around the mean and the same goes for the maximum volume growth rate parameter (VGR_{max}).

The large dataset presented in Table 1 is used to compute Spearman's correlation matrix between impact conditions parameters and gel block metrics. The correlations obtained and statistical significance values are presented in Fig.

7. The strong monotonic relationship between variables is quantified by Spearman's correlation coefficient ρ using a colour scale from -1 to 1. Whereas the alpha risk is fixed to 0.05 indicated with "*", more restrictive alpha risks set at 0.01 and 0.001 are illustrated with "**" and "***" respectively. Correlation coefficient values located inside the black rectangle drawn in Fig. 7 are of interest. Robust relations are determined for a ρ value greater than 0.8 and a *p-value* less than 0.001. Thus, correlations exist between gel block metrics and impact conditions metrics. To go further, each suitable correlation is plotted highlighting eight LLKE projectiles and their respective power fitting functions (see Fig. 8). Among simple mathematical models, the power law remains the best model to describe the correlations according to the R-squared coefficient of determination.

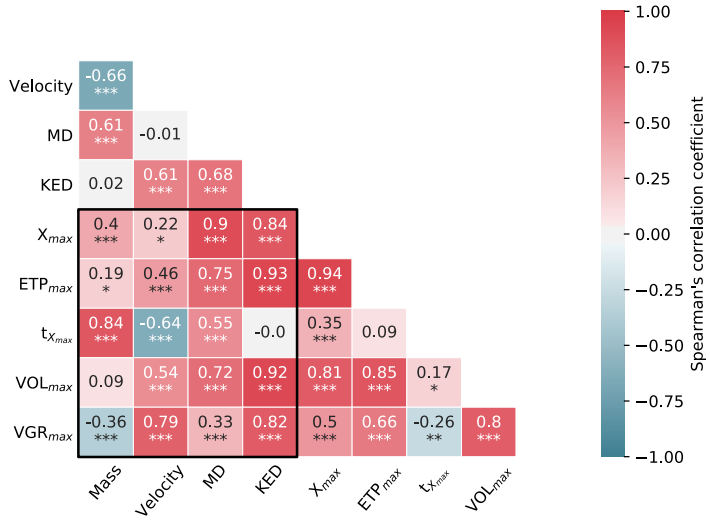


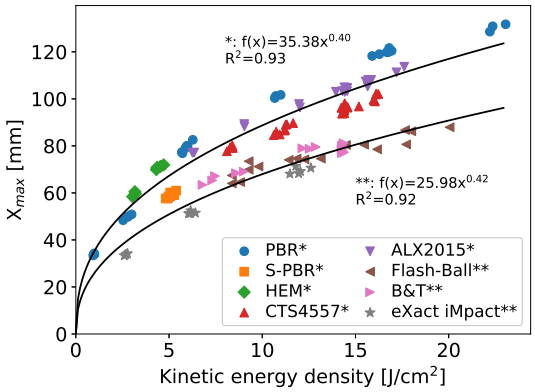
Figure 7: Spearman's correlation coefficient between experimental metrics linked to the gel and impact conditions parameters, represented by a colour scale. The statistical significance between these parameters is indicated using: $^{\star}p < 0.05$, $^{\star\star}p < 0.01$ and $^{\star\star\star}p < 0.001$. A statistical analysis based on N=138 data points.

Fig. 8a and 8b aim to show the relations between X_{max} and the kinetic energy density as well as the momentum density. The kinetic energy is often used to describe impact conditions. However, the kinetic energy needs to be normalised with respect to the projectiles' cross-section area to compare impacts. Depending on the projectile's stiffness, the projectile kinetic energy is not entirely dissipated by the gel block deformation, which can be characterised by

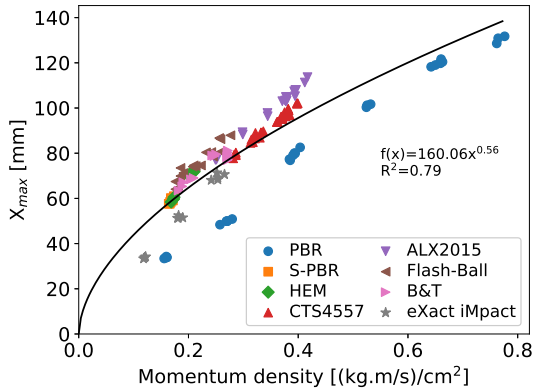
X_{max}. Fig. 8a displays two separate data groups related to stiff (*) and soft (**) projectiles, their respective power fitting functions and R-squared coefficient of determinations. This plot highlights the fact that using kinetic energy density to describe an impact condition is not relevant. In fact, a given kinetic energy density can cause a completely different outcome to the target and the same applies to a human body. Fig. 8a also emphasises that CTS4557 and ALX2015 hybrid LLKE projectiles follow the trend curve of plastic projectiles. This may be explained by a stiff rubber nose used to design these projectiles. Therefore, they behave just like rigid projectiles where the projectile kinetic energy is solely dissipated by the gel block deformation. These conclusions illustrate the importance of using a ballistic target to assess ballistic impacts and projectiles. Fig. 8b shows the correlation between momentum density and X_{max} regardless of the nature of the projectile. A single power fitting function is sufficient to describe this relation. However, data related to high mass PBR projectile deviates from the trend curve. The latter remains trustworthy for projectiles mass ranging between 30 and 60 g. This observation should alert researchers when using momentum density values for projectile design perspectives. An increasing monotonic relationship exists between $t_{X_{max}}$ metric and the projectile mass, irrespective of the projectile nature and its impact velocity (see Fig. 8c). Even though a power function accurately describes this correlation, it does not allow further impact analysis. For a given mass, a similar t_{max} value can be obtained, while a large discrepancy in X_{max} may appear. Therefore, t_{max} is not a relevant metric to examine ballistic impacts, neither is the projectile mass. The conclusions drawn for the correlation between X_{max} and kinetic energy density apply to the ETP_{max} metric. Two distinct power fitting models are identified for stiff and soft LLKE projectiles (see Fig. 8d). Knowing ETP_{max} metric is comparable to the viscous criterion, widely used in biomechanical analyses, this measurement and these correlations with R-squared values above 0.9 are of interest. Fig. 8e outlines a unique strong relationship between VOL_{max} and kinetic energy density, regardless of the projectile's stiffness. This outcome may be explained by the effect of vertical expansion of the gel wall in VOL_{max} values. As

indicated previously through Fig. 8a, for a given kinetic energy density, soft projectiles have lower X_{max} values than stiff ones. However, deformable projectiles due to their soft material nature are subjected to a transverse deformation when impacting the gel block. Hence, the gel wall has a larger vertical expansion using deformable projectiles, which plays a significant role in the calculation of VOL_{max} values. Even though VOL_{max} metric presents a larger scattering for a given impact condition (see Fig. 6b), this variable still remains an interesting measurement to globally describe a ballistic impact. A correlation between VGR_{max} metric and the projectile kinetic energy density is therefore determined which can be captured by a power fitting function (see Fig. 8f). As reflected in Fig. 4d, the VGR_{max} is obtained at the early stages of ballistic impacts when the gel wall velocity is close to the incident projectile velocity. It is thus consistent to find that the maximum rate in volume change correlates with the projectile kinetic energy density irrespective of the projectile's stiffness. Experimental data remains scattered and a low R-squared value of 0.63 is computed. Consequently, VGR_{max} and this relation cannot be considered in future experimental analyses and in the identification of suitable shooting parameters.

(a)



(b)



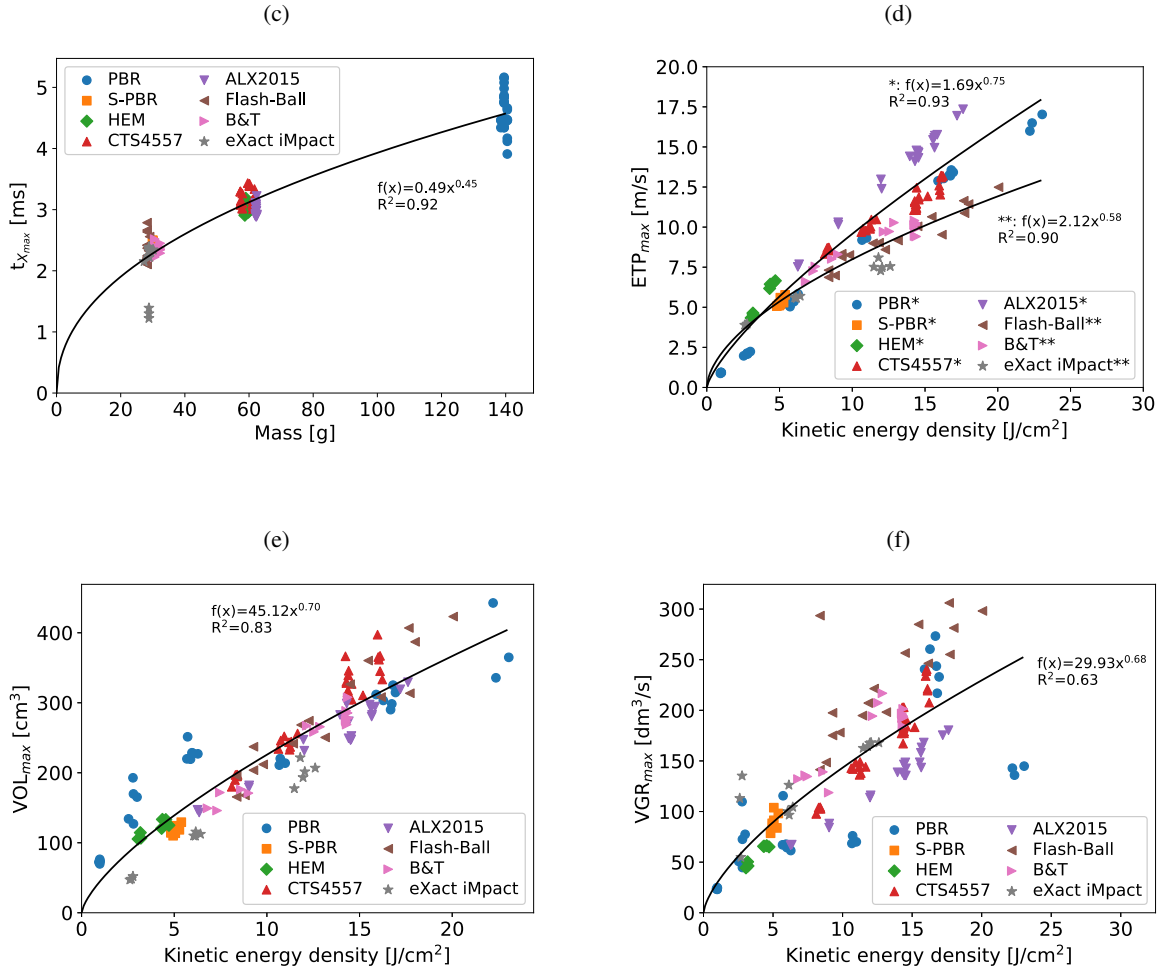


Figure 8: Plots of experimental metrics related to the ballistic target as a function of various impact parameters for eight different LLKE projectiles and respective power fitting functions.

These correlations highlight the interest of using a convenient ballistic target like the SEBS gel material in order to thoroughly assess ballistic impacts and LLKE projectiles. Among the experimental metrics that can be determined during ballistic tests, the most relevant are summarised hereafter:

- the maximum gel wall displacement X_{max};
- the maximum energy transfer parameter value ETP_{max};
- the maximum displaced volume when reaching the maximum gel wall displacement VOL_{max}.

They are chosen for their statistical robustness and their abilities to draw a distinction between stiff and soft projectiles. Moreover, the ETP_{max} metric is analogous to the viscous criterion, used to predict human torso injuries. For a given projectile, considering its cross section and X_{max}, the VOL_{max} metric can depict how it interacts with the gel block. In spite of these outcomes, how may researchers exploit these relations to design projectiles, whilst taking into account biomechanical aspects and related risk of injuries? In the next part, the authors attempt to address this major issue by investigating case reports available in the literature.

3.3. Recreation of case reports and method for developing design guidelines for LLKE projectiles

Among the 138 impact conditions applied to gel blocks, three sets of impact conditions come from case reports described in open literature. The first one, called " Case 1 " defines the impact condition of the PBR projectile at an initial velocity of 40 m/s (see Table 1). The same impact condition was applied to various post-mortem human subjects (PMHS) resulting in each case in an AIS score of 2 or 3 (1998 AIS injury scale) based on rib fractures [8]. The second (" Case 2 ") is described by Kobayashi and Mellen [4] involving the projectile eXact iMpact™ at an impact velocity of 95 m/s. This impact condition induced a lung contusion to a living male (1998 AIS score=3). The third (" Case 3 ") is described by Wahl et al. [5], where the Flash-Ball® projectile caused a heart and lung contusion (1998 AIS score=3) when impacting a living male at a velocity of 120 m/s. These three impact conditions are highlighted in Fig. 9 through the relevant correlations previously identified. Only the power fitting functions and respective 95% confidence intervals are plotted clarifying the three diagrams. The fact that these three cases are the only ones available in the literature may imply that they corresponded to low-probability events or to subjects with atypical vulnerabilities. Table 4 summarises mean experimental metrics values and their standard deviation obtained for each case report in brackets. Although three case reports have been recreated on gel blocks, it is not sufficient to compute the risk of injury due to an impact. Numerous case reports are required where impact conditions and observed injuries

are known. As illustrated by Fig. 10, this could first lead to a logistic regression analysis between gel experimental metrics and the occurrence of serious injuries. Secondly, it could provide, for instance, threshold injury risks at 10, 50 or 90% for experimental metrics. Finally, dependable mass-velocity guidelines could be drawn up to screen LLKE projectiles before their field deployment. However, testing projectiles on SEBS gel blocks still remains mandatory to obtain precise measurements leading to the adjustment of shooting parameters and safety distances.

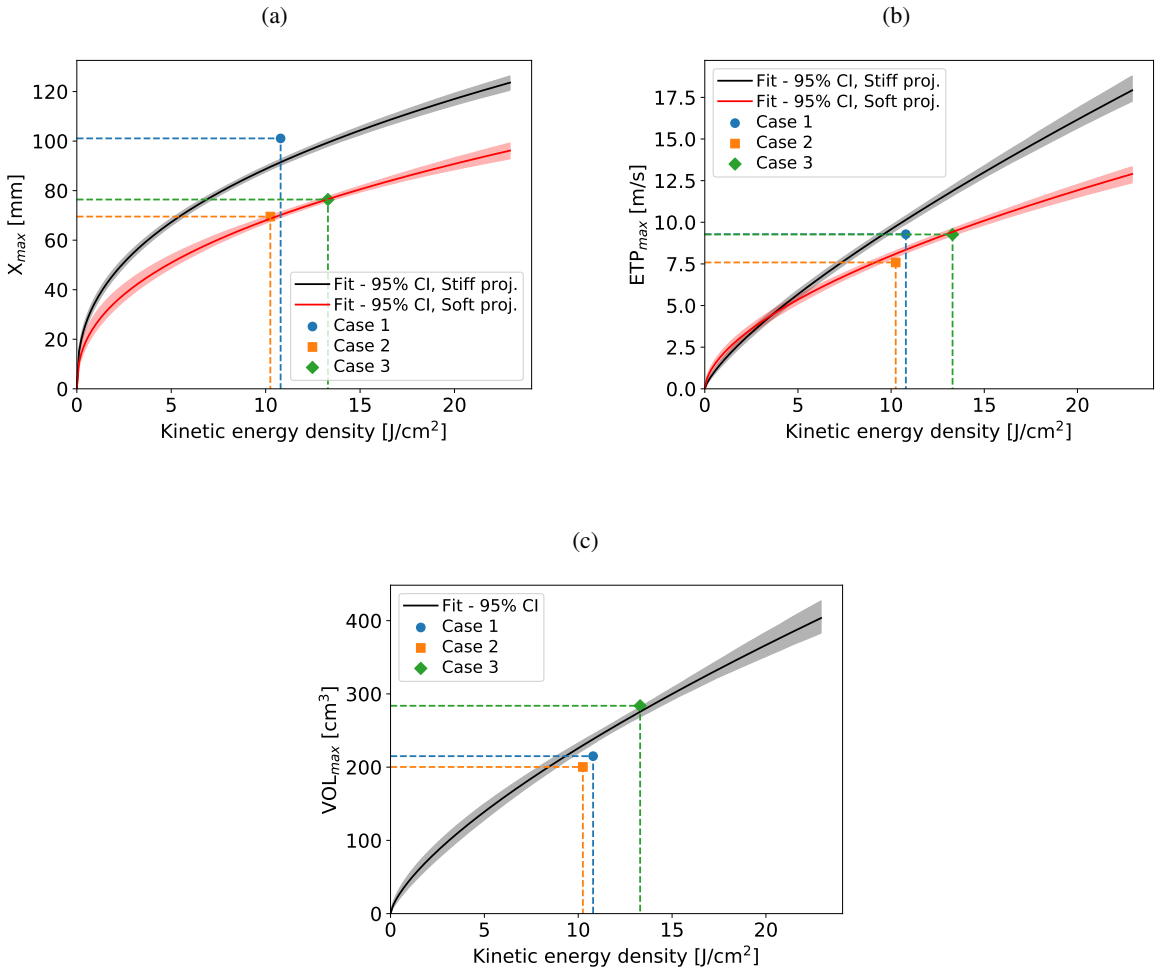


Figure 9: Plots of power fitting functions and respective 95% confidence intervals between experimental metrics and various impact parameters, with respect to stiff and soft projectiles, and case reports values.

Table 4: Experimental metric values (standard deviations are mentioned in brackets) and 1998 AIS scores (thoracic region) according to case reports mentioned in the literature.

	Experimental metrics				
	X_{max} [mm]	ETP_{max} [m/s]	VOL_{max} [cm^3]	AIS score (thorax)	Reference
Case 1	101.1 (0.7)	9.3 (0.1)	215.0 (4.8)	2-3	Bir and Viano [8]
Case 2	69.5 (1.4)	7.6 (0.3)	200.2 (16.3)	3	Kobayashi and Mellen [4]
Case 3	76.4 (3.4)	9.3 (0.7)	283.8 (38.9)	3	Wahl et al. [5]

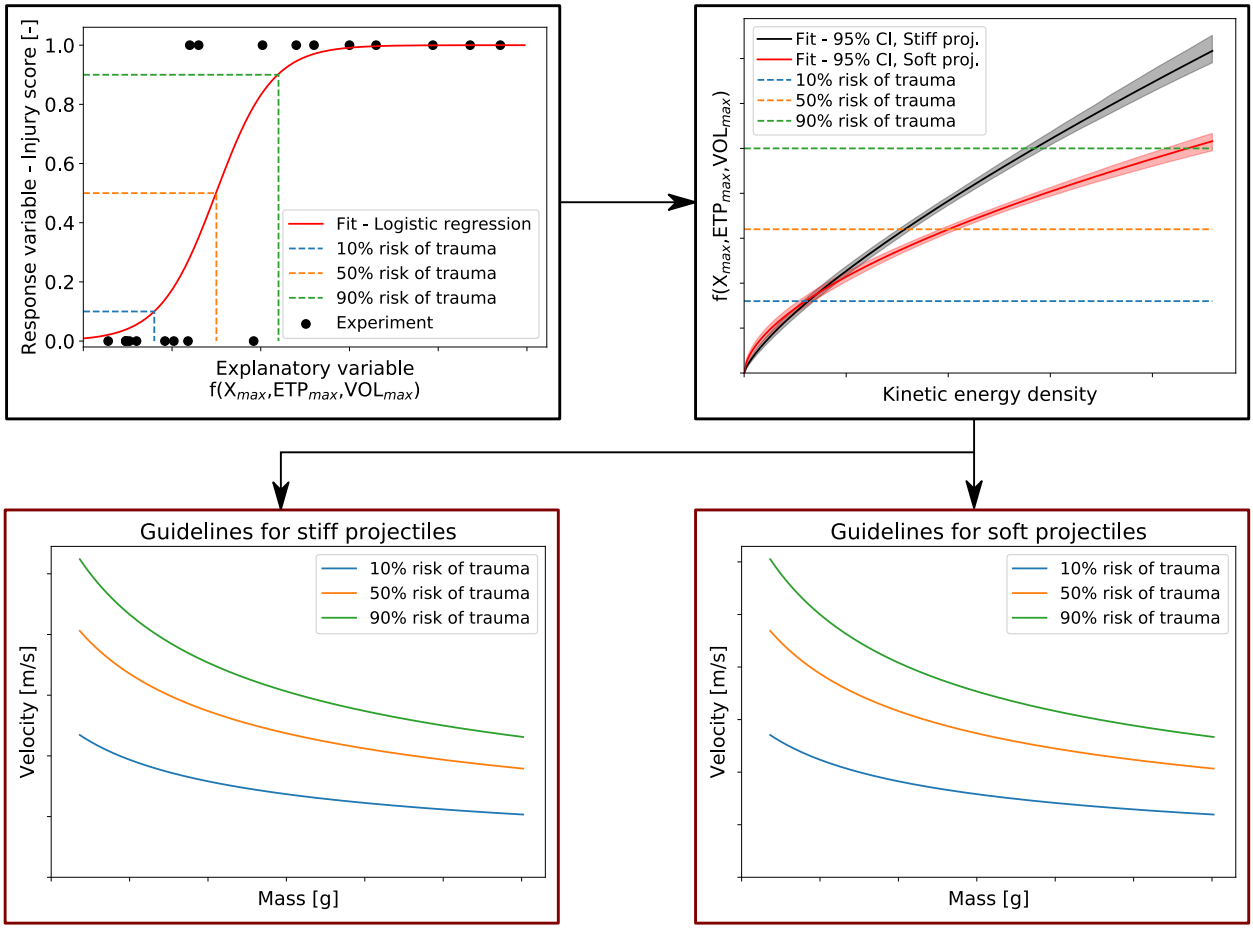


Figure 10: Flow chart describing the potential of reporting case fields with sustained injuries to determine mass-velocity guidelines for projectiles at different risks of trauma.

4. Conclusion

The SEBS gel material is proposed as a novel transparent ballistic target to assess non-penetrating ballistic impacts and LLKE projectiles before their use by law enforcement agencies across the world. High-speed imaging and a

specific image processing routine coded in MATLAB capture the dynamic gel wall displacement profile over time. Several metrics are worked out to describe impacts such as the maximum gel wall displacement or the energy transfer parameter value. The mechanical consistency and batch-to-batch reproducibility of the target are verified by an ANOVA and statistical comparisons of repeated shots performed on gel blocks produced in different years.

A statistical analysis is then conducted based on the dataset generated by 138 impact conditions of soft and stiff LLKE projectiles applied to gel blocks. Spearman's correlation matrix is computed in order to identify the most relevant relations from a pool of metrics like the maximal energy transfer parameter or the projectile kinetic energy density. It highlights the requirement to use a ballistic target to quantify the effects of a projectile rather than kinetic energy or momentum. Dependable power law functions have been identified between projectile kinetic energy density and the maximum gel wall displacement, the maximum ETP value as well as the maximum displaced volume according to the projectile's stiffness.

Three case reports involving commercially available LLKE projectiles have been recreated on the ballistic target. The specific impact conditions related to those cases have resulted in serious thoracic injuries as rib and sternal fractures as well as lung and heart contusions. The need to gather case studies is essential to obtain reliable statistical outcomes. It could lead to the identification of mass-velocity guidelines for projectiles as a function of their stiffness. Quantifying the wounding potential of any LLKE projectiles would be the focus of future investigations which could benefit numerous actors involved in the field of defence and safety.

Conflict of Interest

The authors have no conflicting interests regarding this paper.

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Author Statement

Anthony Bracq: Methodology, Formal Analysis, Investigation, Writing - Original Draft, Visualization, Writing Review & Editing

Rémi Delille: Conceptualization, Methodology, Investigation,

Christophe Maréchal: Methodology, Investigation, Writing Review & Editing

Benjamin Bourel: Formal Analysis, Software, Visualization

Franck Lauro: Resources, Supervision, Project Administration

Sébastien Roth: Resources, Supervision, Project Administration

Olivier Mauzac: Formal analysis, Investigation, Resources, Supervision, Project Administration

Declaration of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights

- A polymer gel block is used as ballistic testing medium to interpret non penetrating impacts.
- The transparent target material appears to be insensitive to ageing and is reproducible from batch-to-batch.
- 138 ballistic impacts of eight commercially available less-lethal kinetic projectiles on gel blocks are assessed using high-speed imaging and specific image processing routines.
- Spearman's correlation matrix is computed to identify reliable relations between experimental metrics and projectile kinetic energy/momentum density.
- A procedure for the identification of mass-velocity guidelines is provided for less-lethal kinetic energy projectiles.